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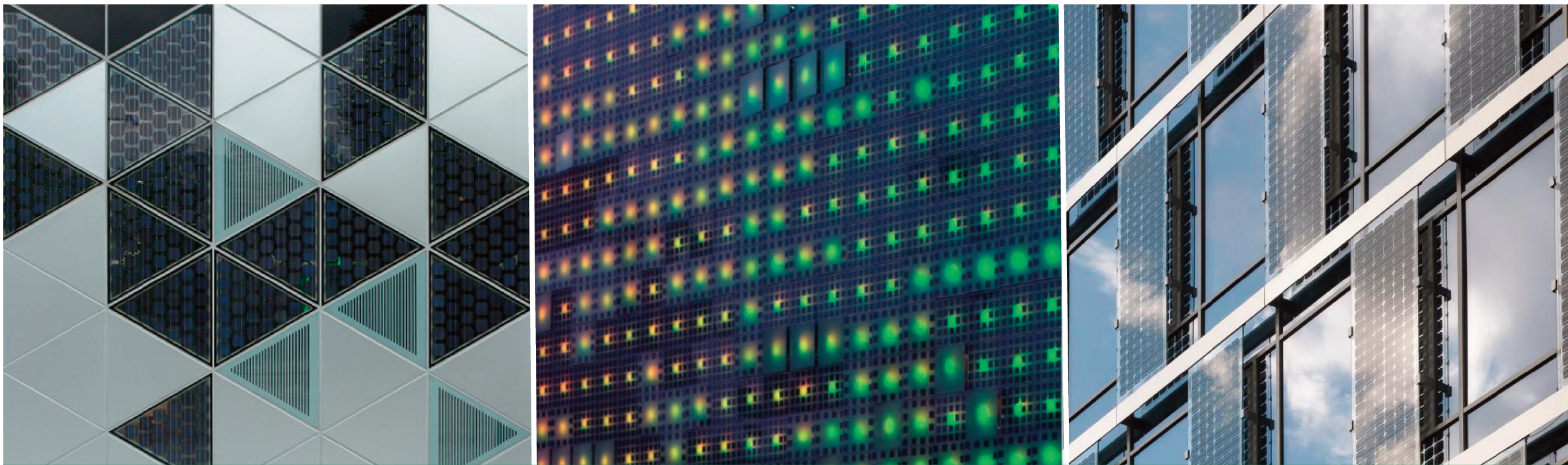
ARCHITECTURE AND PHOTOVOLTAICS
Strategies, technologies and novel components for the building envelope



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INTRODUCTION _ *INTRODUZIONE*

The fight to global warming represents one of the most important challenges that the entire humanity has to face in the coming years. The main cause to this phenomenon is represented by the growing and growing amount of greenhouse gases emitted in the atmosphere and due to the consumption of fossil fuels — coal, oil, and natural gas — that today are around 80% of the energy utilized by men (IEA, 2014). During the XX century, the average temperature on the earth has increased of around 0.8 °C, with local variations even more accentuated, especially at the poles. Extreme weather changes, the retreat of glaciers, the rising of sea levels, the expansion of desert areas are only some of the consequences of this phenomenon, which is destined to grow further, threatening environmental disasters of immeasurable proportions, unless decided, collective actions are undertaken in the fields of energy and of greenhouse gases reduction.

In this framework, world's countries have started to commit more and more intensely to investing in alternative sources of energy than fossil fuels (and, in particular towards renewable energy technologies) and to improving the energy efficiency of industry, transport, and building sectors.

La lotta al cambiamento climatico rappresenta una delle principali sfide che l'umanità dovrà affrontare nei prossimi anni. La causa principale di tale cambiamento è da attribuire alle sempre maggiori quantità di gas serra emessi nell'atmosfera e dovuti al consumo di combustibili fossili — carbone, petrolio e gas naturale — che oggi rappresentano l'80% dell'energia utilizzata dall'uomo (IEA, 2014). Durante il XX secolo, la temperatura media dell'aria sul pianeta è aumentata di 0.8 °C, con variazioni locali ancora più accentuate, specialmente ai poli. Le sempre più estreme variazioni climatiche, lo scioglimento dei ghiacciai, l'innalzamento del livello del mare, l'espansione delle aree desertiche sono solo alcune delle conseguenze di questo fenomeno che rischia di portare a disastri ambientali di proporzioni mai viste se non si interverrà in maniera decisa sui temi dell'energia e della riduzione delle emissioni di gas serra.

In quest'ambito, i paesi del mondo hanno iniziato a impegnarsi in maniera sempre più intensa nella lotta al cambiamento climatico, investendo in forme di energia alternativa (in particolare, sulle rinnovabili) e lavorando per il miglioramento dell'efficienza energetica nei settori dell'industria, dei trasporti e dell'edilizia.

Besides the rising environmental concern, several other reasons put at the center of the contemporary debate the issue of Energy. The availability and control of energy sources are strategically and economically relevant factors for a country and, de facto, the fight for the procurement of oil, in particular, has led to international conflicts that are likely to intensify in the future. Indeed, as the oil crises have reminded, energy requirements are growing and fossil fuels, our main sources of energy, are actually finite, unreliable and, very importantly, they are not available everywhere in the planet: this not only puts into doubt their ability to meet growing energy demand for future generations, but also has to do with the equality and the accessibility of energy for everyone[1].

Having said that, it is no surprise that renewable energy technologies — safe, clean, and potentially infinite sources of energy — have grown remarkably during the last decades and are expected to grow further in the future. In the European Union, for example, the share of energy from renewable sources in gross final consumption of energy almost doubled from 8.3% in 2004 to 15.0% in 2013 (Eurostat, 2015), and is projected to reach the target of 20% by 2020 (EC, 2010).

Speaking more in detail about Photovoltaics (PV), Europe has had since the beginning a leading position regarding both research and innovation, industrial production and cumulative installed capacity[2]. In 2013, with 81.5 GW installed, EU accounted for 59% of world's cumulative PV capacity, with a large share of the market concentrated in the on-site distributed ge-

D'altra parte, non sono solo questioni di carattere ecologico a porre in primo piano il tema dell'energia. La disponibilità e il controllo delle fonti di energia sono fattori di grande rilevanza strategica ed economica per un paese e, di fatto, la lotta per l'approvvigionamento in special modo del petrolio ha condotto a conflitti internazionali che sono destinati a intensificarsi in futuro. Del resto, le richieste energetiche sono in continua crescita e i combustibili fossili, che costituiscono la principale fonte di approvvigionamento energetico per l'umanità, sono in realtà finiti, inaffidabili e soprattutto non disponibili in ogni luogo del pianeta: questo non solo mette in dubbio la loro capacità di rispondere alla crescente domanda di energia per le generazioni future, ma ha anche a che fare con l'uguaglianza e l'accessibilità dell'energia per tutti[1].

Non è pertanto una sorpresa che le tecnologie basate sull'impiego di fonti d'energia rinnovabili — sicure, pulite e potenzialmente infinite — siano cresciute significativamente nel corso degli ultimi decenni e siano caratterizzate da previsioni di ulteriore crescita. Nell'Unione Europea, per esempio, la percentuale di energia da fonte rinnovabile sul consumo lordo di energia è quasi raddoppiata passando dall'8.3% del 2004 al 15% del 2013 (Eurostat, 2015), con l'obiettivo di raggiungere il 20% entro il 2020 (EC, 2010).

Per quanto riguarda il Fotovoltaico (FV), l'Europa ha da sempre avuto una posizione di leadership nell'ambito della ricerca, dell'innovazione e della produzione industriale nonché in termini potenza installata[2]. Nel 2013, l'UE contava 81.5 GW di potenza FV installata, corrispondenti al 59% della potenza a livello mondiale, con un'ampia quota del mercato dedicata alla genera-

neration in the residential, commercial and industrial building-mounted segments, against the 34% of utility-scale, centralized, ground-mounted systems. Besides the scale, ranging from less than 10 kW capacity for residential application to capacity in excess of 1 MW for ground-mounted plants (MITei, 2015), an important difference is that «…*locating the photovoltaic cells on the roofs of homes, industries, and other buildings would reduce the need for additional land […] and reduce transmission costs*…» (Pimentel et al., 2002). This great share of building-mounted PV systems is obviously the result of EU policies, which in turn reflected into government initiatives at local and national level, pushing towards decentralized energy models based on renewable sources (electricity from the sun, in the specific case of photovoltaics). Moreover, it is also in line with the objectives of the EU as regards the maximization of the energy efficiency of the building stock[3], i.e. the most energy demanding sector, accounting for roughly 40% of worldwide greenhouse gas emissions.

The more and more widespread use of Photovoltaics into the building stock brought along several implications regarding the best way to integrate such systems for the generation of clean electricity into buildings, by taking into consideration not only the economic and technical aspects, but also those related to the appearance and architectural quality of buildings and cities.

The most conventional and most widespread systems, simply added on top of the building roof after it is completed, have often been criticized for their unpleasant aesthetic result.

zione distribuita "in situ" sugli edifici dei settori residenziale, commerciale e industriale, contro il 35% relativo agli impianti di larga scala, centralizzati e installati al suolo. Al di là della scala, che va da meno di 10 kW di potenza per applicazioni residenziali a capacità maggiori anche di 10 MW per impianti montati a terra (MITei, 2015), un'importante differenza sta nel fatto che «...posizionare le celle FV sui tetti di case, industrie e altri edifici riduce la necessità di suolo [...] e i costi di trasporto dell'energia...» (Pimentel et al., 2002). Questa grande percentuale di impianti FV installati sugli edifici è chiaramente il risultato delle politiche dell'Unione che si sono a loro volta riflesse in una serie di iniziative dei governi a livello nazionale e locale, dirette verso modelli energetici decentralizzati e basati sull'impiego di fonti rinnovabili. Inoltre, essa è anche in linea con gli obiettivi dell'UE relativi alla massimizzazione dell'efficienza energetica del settore edilizio[3], che è il settore maggiormente energivoro, responsabile di circa il 40% delle emissioni di gas serra nell'atmosfera.

Il sempre più diffuso impiego del fotovoltaico nel settore edilizio ha portato con sé una serie di implicazioni relative alla maniera migliore con cui integrare questi sistemi per la generazione di elettricità negli edifici, non soltanto tenendo in considerazione gli aspetti tecnici ed economici, ma anche valutando quelli legati all'estetica e alla qualità architettonica degli edifici e delle città.

I sistemi fotovoltaici più convenzionali e, al tempo stesso, più diffusi, semplicemente "aggiunti" in corrispondenza delle coperture degli edifici, sono stati spesso criticati per il loro risultato estetico.

However, during the last two decades, a new family of multifunctional building and photovoltaic products, specifically developed for replacing technical elements of the building envelope, has emerged and has become one of the fastest growing sectors of the market: the Building Integrated PhotoVoltaics (BIPV). The characteristics of the BIPV systems become an integral part of the design process, not only in terms of energy production but also, more in general, as regards the aspects directly related to the functionality, energy efficiency and appearance of the building.

Several new outstanding building **concepts** as well as built examples of the integration of solar PV technology in buildings can be individuated in the architectural panorama of the last two decades. The joint collaboration of the research, building and photovoltaic industries allowed for the development of novel solar **technologies** — such as, for example, the so-called third-generation solar cells — characterized by properties that are particularly adapted in the perspective of building integration (lightness, transparency, flexibility, aesthetic versatility, etc.). On the other hand, new BIPV **products** have been developed, specifically studied to substitute "conventional" building materials and components as well as to enhance their properties in the perspective of Zero-Energy Buildings.

Nevertheless, BIPV still represents a niche in the PV sector and various barriers, related to mere cost-efficiency ratio as well as psychological and social factors (Heinstein et al, 2013) need to be overcome in order to realize its full potential, which goes beyond the production of clean energy, but

Nel corso degli ultimi due decenni è emersa una nuova famiglia di prodotti multifunzionali, fotovoltaici ed edilizi, specificamente sviluppati per sostituire elementi tecnici dell'involucro edilizio. Questa è diventata uno dei settori del mercato del fotovoltaico con la più rapida crescita: il Building Integrated PhotoVoltaics (BIPV). Le caratteristiche dei sistemi BIPV diventano parte integrante del processo progettuale non solo per gli aspetti concernenti la produzione di energia, ma anche, più in generale, per quelli più propriamente legati alla funzionalità, all'efficienza energetica e all'estetica dell'edificio.

Una serie di nuovi e interessanti ***concept*** *e di esempi realizzati di integrazione architettonica del FV negli edifici si possono individuare nell'ambito del panorama architettonico degli ultimi due decenni. La collaborazione fra il mondo della ricerca e le industrie fotovoltaica ed edilizia ha permesso lo sviluppo di* ***tecnologie*** *solari innovative — fra cui, ad esempio, le celle solari di terza generazione — caratterizzate da proprietà che si prestano particolarmente all'integrazione architettonica (leggerezza, trasparenza, flessibilità, versatilità estetica, ecc...). Dall'altro lato, sono stati sviluppati nuovi* ***prodotti*** *BIPV, specificamente studiati per sostituire materiali e componenti edili "convenzionali" e, al contempo, potenziarne le proprietà nell'ottica degli edifici a energia zero (Zero-Energy Buildings).*

Nonostante questo, il BIPV rappresenta una nicchia del mercato fotovoltaico e sono ancora numerose le barriere, legate al rapporto costo/efficienza nonché a fattori psicologici e sociali, che è necessario superare affinché questo realizzi appieno il suo potenziale che va al di là della produzione di also deals with the sustainable transformation and valorization of cities and buildings. A great collaborative effort of researchers, architects, engineers, building materials and PV manufacturers is needed in order to help newest technologies disrupt the market and to boost the development of novel building solutions, able to respond to the most diversified requirements.

Starting from these considerations, the present work deals with the architectural integration of photovoltaics for the energy retrofit of the existing building stock and the construction of new Zero Energy Buildings. The main objective is the study of strategies and technologies for the integration of photovoltaics in buildings, particularly with regard to third-generation solar technologies, and, subsequently, the definition of a novel, multifunctional component for the building envelope integrated with third-generation Dye-sensitized Solar Cells (DSC).

The dissertation is divided into two parts. In the first part, the architectural integration of photovoltaics was investigated both at technology, product and concept level. The research indeed focused on an in-depth study of products from the BIPV market, underlining differences, limits and potentialities of each PV technology and keeping an eye on the achievements that were possible on the architectural level thanks to the progresses in the solar energy field and the collaboration between building and photovoltaic industries. At the same time, significant attention was also given to the analysis of a consistent number of case studies, i.e. examples of either new construction or retrofit where interesting solutions for the inte-

energia, riguardando anche la trasformazione sostenibile e la valorizzazione del territorio. Occorre la collaborazione di ricercatori, architetti, ingegneri, produttori di materiali edili e prodotti FV, per far sì che le più recenti tecnologie si affermino sul mercato e per incentivare lo sviluppo di nuove soluzioni per gli edifici, in grado di rispondere ai più svariati requisiti.

A partire da queste considerazioni, il presente lavoro di tesi riguarda l'integrazione architettonica del fotovoltaico per il retrofit energetico del patrimonio edilizio esistente e per la costruzione di nuovi Zero-Energy Buildings. Il principale obiettivo ha riguardato lo studio di strategie e tecnologie per l'integrazione del fotovoltaico negli edifici, con particolare attenzione verso le tecnologie solari di terza generazione e la successiva definizione di un componente multifunzionale innovativo per l'involucro edilizio integrato con Dye-sensitized Solar Cells (DSC).

La dissertazione è divisa in due parti. Nella prima, il tema dell'integrazione architettonica del fotovoltaico è stato analizzato sia a livello di prodotto/tecnologia sia a livello di concept e progetto. La ricerca si è infatti concentrata sullo studio del mercato BIPV, sottolineando differenze, limiti e potenzialità di ciascuna tecnologia fotovoltaica e ponendo l'accento sui risultati ottenuti, sul piano dell'architettura, grazie ai progressi tecnologici registrati e alla collaborazione fra industria fotovoltaica ed edilizia. Particolare attenzione, inoltre, è stata rivolta all'analisi di un numero consistente di casi studio, ossia edifici di nuova costruzione o interventi di retrofit in cui è stato possibile rintracciare interessanti soluzioni per l'integrazione gration of PV have been individuated. Starting from the analysis of the market, of emblematic examples of PV integration in the contemporary architectural panorama and of the related design and technical solutions, it has been possible to provide a wide picture of the theme and to make some considerations regarding new trends observed and possible developments. Some criteria for the assessment of the level of photovoltaic integration in buildings have also been elaborated, with the aim to incentivize a more conscious use of this renewable energy technology in architecture.

The second part of the thesis moved from the results and considerations elaborated in the first part and regards the technological optimization and energy performance analysis of a novel, translucent component for building-integrated photovoltaics: namely, a multifunctional panel made of glass blocks integrated with third-generation DSCs (Corrao et al., 2013)[4]. Novel thermally optimized glass block configurations, integrated with DSC modules with different colors and transparency levels, were analyzed with the support of different softwares (Comsol Multiphysics, WINDOW and Zemax), in order to assess their thermal insulation, optical transmittance, solar energy transmittance, and electricity production. Subsequently, the benefits deriving from the installation of this product in place of the glazed façades of an office building located in Palermo, were assessed with the support of a building performance simulation software (DesignBuilder). The aim was to evaluate the energy-saving potential of the DSC-integrated glass blocks as well as to make an estimation of their yearly electricity production.

del fotovoltaico. A partire dall'analisi del mercato, di esempi emblematici di integrazione del fotovoltaico nel panorama architettonico contemporaneo e delle soluzioni tecniche e progettuali in essi adottate, è stato possibile tracciare un quadro ampio sul tema e fare alcune valutazioni sulle tendenze riscontrate e sui nuovi sviluppi possibili. Sono stati inoltre elaborati alcuni criteri per la valutazione del grado di integrazione del fotovoltaico negli edifici, utili a incentivare un uso più consapevole di questa tecnologia per la produzione di energia rinnovabile nell'ambito dell'architettura.

La seconda parte del lavoro ha preso le mosse dai risultati e dalle considerazioni elaborate nella fase precedente e ha riguardato l'ottimizzazione tecnologica e l'analisi delle prestazioni energetiche di un componente innovativo traslucido per il BIPV: un pannello multifunzionale in vetromattoni integrati con celle di terza generazione DSC (Corrao et al., 2013)[4]. Nuove configurazioni del prodotto, ottimizzate dal punto di vista dell'isolamento termico e integrate con moduli DSC di differenti colori e livelli di trasparenza sono state analizzate, attraverso l'impiego di differenti software (Comsol Multiphysics, WINDOW e Zemax), allo scopo di valutarne le prestazioni di isolamento termico, trasmissione luminosa e solare, produzione elettrica. Inoltre, si sono valutati, per mezzo di un software per la simulazione energetica (DesignBuilder), i benefici derivanti dall'installazione di questo prodotto in luogo delle facciate vetrate di un edificio per uffici della città di Palermo, al fine di comprendere il potenziale risparmio energetico connesso all'utilizzo dei vetromattoni integrati con DSC nonché di stimarne la produzione elettrica annuale.

The research has been carried out at the Department of Architecture of the University of Palermo, although a part of it has been conducted with the collaboration of the Strategic Research Centre on Zero Energy Buildings of Aalborg University, in Denmark, where the candidate spent part of the doctoral programme as guest PhD student[5].

La ricerca è stata condotta presso il Dipartimento di Architettura dell'Università di Palermo, sebbene una parte di essa sia stata portata avanti con la collaborazione dello Strategic Research Centre on Zero Energy Buildings dell'Università di Aalborg, Danimarca, presso cui il candidato ha trascorso parte del triennio del Dottorato[5].

Notes

1) The challenge of the Energy Equality is fundamental, if we think that, around 1.3 billion people, corresponding to 18% of world's population, did not have any access to electricity in 2011 (RSC, 2015).

2) However, EU is expected to lose its leadership in the next future, due to the notable increase expected for the Chinese market (EPIA, 2014)

3) According to these objectives, by 2020, all new buildings in the Union will have to be nearly zero-energy buildings and the «...*very low amount of energy required should be covered to a very significant extent by energy from renewable sources [...] produced on-site or nearby...*» (EPBD, 2010).

4) The work is inserted in a wider research project, carried out at the Department of Architecture of the University of Palermo, aimed at the performance optimization of the glass block in order to allow for its use in the construction of translucent, sustainable building envelopes (project title: "Incremento prestazionale di componenti edilizi per la realizzazione di involucri sostenibili", coordinator: prof. Rossella Corrao).
The development and commercialization of this building component is the main objective of the technological start-up company and academic spin-off of the University of Palermo SBskin. Smart Building Skin s.r.l. (www.sbskin.it).

5) From December 2013 to April 2014, under the supervision of Prof. Per Heiselberg.

Note

1) Quella dell'Energy Equality è una sfida fondamentale, se si pensa che circa 1.3 miliardi di persone, corrispondenti al 18% della popolazione mondiale, non avevano alcun accesso all'elettricità nel 2011 (RSC, 2015).

2) Comunque, si prevede che l'Europa perderà la sua leadership nel prossimo futuro, a causa della notevole crescita attesa dal mercato cinese (EPIA, 2014)

3) Sulla base di questi obiettivi, entro il 2020, tutti i nuovi edifici nell'UE dovranno essere a energia quasi zero e la «...bassissima quantità di energia (da essi) richiesta dovrà essere coperta in misura significativa da energia da fonte rinnovabile [...] prodotta in situ o nelle immediate vicinanze...» (EPBD, 2010).

4) Il lavoro si inserisce in una più vasta ricerca, condotta presso il Dipartimento di Architettura dell'Università di Palermo e finalizzata all'ottimizzazione energetica del vetromattone per permettere il suo utilizzo nell'ambito della costruzione di involucri edilizi traslucidi e sostenibili (titolo del progetto: "Incremento prestazionale di componenti edilizi per la realizzazione di involucri sostenibili", coordinatore: prof.ssa Rossella Corrao).
Lo sviluppo e la commercializzazione del componente edilizio qui presentato è il principale obiettivo della start-up tecnologica e spin-off accademico dell'Università di Palermo, SBskin. Smart Building Skin s.r.l. (www.sbskin.it).

5) Da Dicembre 2013 ad Aprile 2014, sotto la supervisione del Prof. Per Heiselberg.

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PART I
State of the Art

CHAPTER 1
Solar Energy in Buildings
L'Energia solare negli edifici

ABSTRACT_ITA - *A partire dalla definizione del quadro internazionale contemporaneo nell'ambito della lotta al cambiamento climatico, questo capitolo contiene un breve excursus su alcune delle principali direttive a livello nazionale e internazionale sull'efficienza energetica e sull'impiego delle energie rinnovabili, con particolare attenzione al settore edilizio. Secondo la European Directive on Energy Performance of Buildings, dal 2020 in poi, tutti gli edifici di nuova costruzione dovranno essere a energia quasi zero (nearly Zero-Energy Buildings, nZEB), ossia caratterizzati da consumi energetici minimi, coperti nella maggiore misura possibile da energia rinnovabile prodotta in loco o nelle immediate vicinanze.*

In quest'ambito, si è fatto sempre più strada, all'interno del panorama contemporaneo, il concetto di Architettura Solare, che prende le mosse dall'urgenza di ridurre le emissioni di gas serra nell'atmosfera del settore edilizio e dalla consapevolezza dell'enorme potenziale energetico proveniente dalla Natura e, in particolare, dal Sole.

Questo capitolo introduce e discute nel dettaglio il tema dell'Architettura Solare, tenendo in particolare considerazione tutte quelle strategie che possono essere messe in campo per massimizzare i benefici che derivano dall'utilizzo, diretto o indiretto, dell'energia del sole per l'ottimizzazione dell'efficienza energetica degli edifici. Particolare attenzione è riservata alle soluzioni tecniche e alle tecnologie che coinvolgono in maniera diretta l'involucro edilizio, prendendo in esame sia soluzioni passive che tecnologie attive, come il Fotovoltaico (FV) e il Solare Termico (ST). Per quanto riguarda, in particolare, il fotovoltaico, alcuni aspetti tecnici e normativi sono introdotti e trattati con un maggiore dettaglio.

L'obiettivo di questo capitolo è di tracciare un quadro generale dell'ambito tecnico e scientifico all'interno del quale questo lavoro è inserito, introducendo e definendo nel dettaglio termini e concetti che saranno ripresi successivamente nel corso della tesi.

ABSTRACT_ENG - *Starting from an outline of the contemporary international framework related to the fight to global warming, this chapter entails a brief overview of some of the main international and national directives regarding the energy efficiency and the use of renewable energies, with particular focus on the building stock. According to the European Directive on Energy Performance of Buildings, by 2020, all new constructions will have to be nearly Zero-Energy Buildings (nZEBs), i.e. characterized by minimized energy consumption that are covered to a very significant extent by renewable sources produced on-site or nearby.*

In this field, the concept of Solar Architecture — moving from the urgency to reduce greenhouse gas emissions in the building stock and from the conscience of the enormous energy potential coming from nature and, in particular, from the sun — gained a central attention in contemporary architectural debate.

In this chapter, Solar Architecture is introduced and discussed, by taking into particular account all those design strategies that can be put in place for the maximization of the benefits deriving from the use, either direct and indirect, of solar energy into buildings for the optimization of their energy efficiency, with particular focus on technical and technological solutions for the building envelope. Passive strategies and active technologies, such as Photovoltaics (PV) and Solar Thermal (ST), are handled. In particular, as regards the photovoltaic technology, technical and regulatory aspects are introduced and treated more in-depth.

The objective is to outline the general framework where this work is inserted as well as to introduce some of the terms and concepts that are resumed later in the work in order to help an easier understanding of the subsequent dissertations.

1.1. Introduction

The exponential growth that, over the last two centuries, have characterized greenhouse gas (GHG) emissions in the atmosphere has reached unsustainable levels, leading towards alarming environmental issues, commonly known as Climate Change. Stabilizing GHG concentration in the atmosphere «...*at a level that would prevent dangerous anthropogenic interference with the climate system...*»[1] became an urgent global priority, which is pushing world's countries towards large investments in alternative sources of energy and, in particular towards renewable technologies, devestments in "conventional" carbon-based energy sources, and interventions for the energy efficiency optimization in all sectors (from manufacturing to building and transport industries).

By October 2015, over 150 countries, representing around 90% of global fossil fuel demand and almost 80% of global fossil fuel production, have submitted climate change pledges[2] for the period post-2020. If the declared commitments are respected, this will lead to a growing distance — already occurred in 2014 — between the electricity demand, directly linked with the worldwide economic growth, and the GHG emissions that would remain steadily flat after 2015, as shown in the graph of the International Energy Agency, IEA (Figure 1.1, left). The European Union, for example, has declared the intention to decrease domestic GHG emissions by at least 40% below 1990 levels by 2030, whereas the United States have committed towards a 26-28% reduction in GHG emissions by 2025 with respect to 2005 levels (IEA, 2015); both these two countries have cut significantly their emissions compared to the levels at the beginning of the 21st century (Figure 1.1, right).

Speaking of the European Union, in particular, and of the measures that have already been undertaken to tackle the challenge of the climate change, it is possible to say that its policy on energy and climate realized concretely in March 2007 with the approval, by the governing bodies of Member States, of the Plan 20-20-20 (EC, 2010).

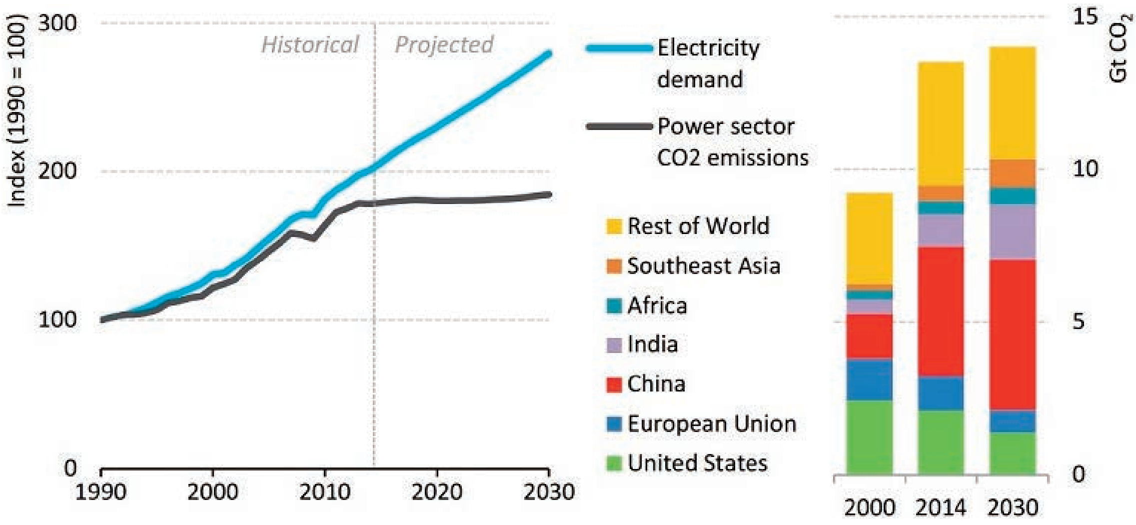


Figure 1.1 - *(left)* Growth in world electricity demand and related CO_2 emissions since 1990 and *(right)* related CO_2 emissions by region (IEA, 2015)

This plan is articulated into three main objectives, to be achieved by the end of 2020:

- 20% reduction of greenhouse-gas emissions;
- 20% reduction of the energy consumption;
- 20% increase of renewable energy sources.

In order to achieve the goals set for 2020, the EU has enacted a series of directives aimed at the energy efficiency in all sectors, further absorbed by diversified initiatives by the Member States, and dedicated specific funds for supporting the spread of Renewable Energy Sources (RES).

The building sector, in particular, accounts for 40% of energy consumption in the European Union (same as in the rest of the world), mainly due to heating, cooling and electricity requirements. Thus, it represents one of the most important sectors — if not the most important one — on which to intervene in order to reduce the EU energy dependency and GHG emissions. Besides, it is still an expanding sector, thus further increasing its energy consumption. In particular, the existing building stock is extremely energy-consuming and today is in need of significant upgrading measures, which represent both a great challenge and opportunity.

In this framework, it is important to mention the European Directive on Energy Performance of Buildings (EPBD)[3] that restates the necessity to improve the overall energy efficiency of new buildings and existing buildings during their significant renovation, calling international attention to the urgency of drawing up national plans for the construction of nearly Zero-Energy Buildings (ZEBs) and taking into account, at the same time, the building typologies and national, regional or local climatic conditions. The EPBD does not define in a specific way what a "nearly zero-energy building"[4] is, unless of stating, in the Article 2, that it is a building «...*that has a very high energy performance...*»[5] and pushing back the decision to fix binding limits to each of the Member States, but it clearly gives important directions in this sense.

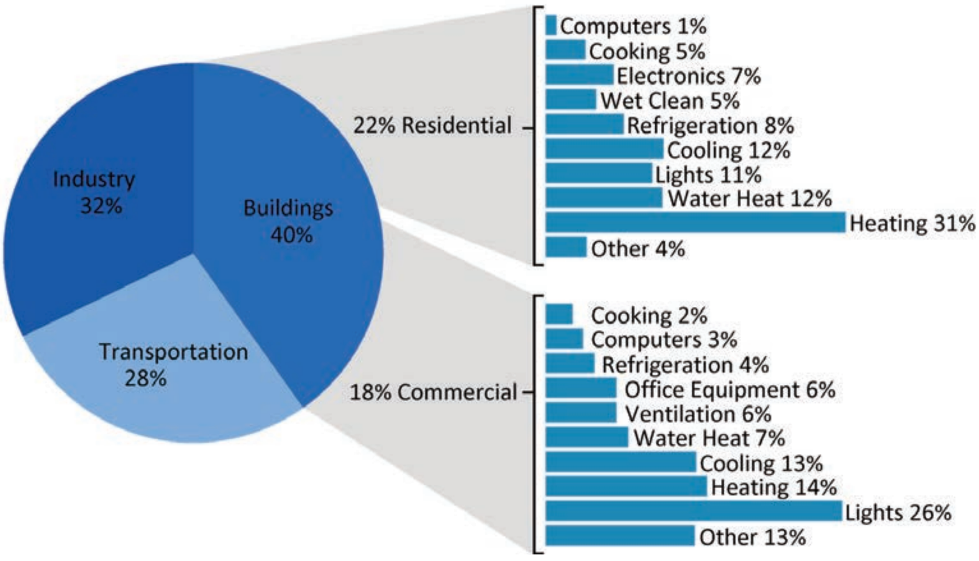


Figure 1.2 - Total Energy Consumption by Sector (re-elaborated from Tulloch, 2009)

In this regard, the directive highlights that «...*the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby...*» (EPBD, 2010).

Having said that, the directive states that the Member States shall ensure that:

- *by 31 December 2020, all new buildings are nearly zero-energy buildings; and*
- *after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings*[6].

The EPBD also involves existing built stock, urging Member States to «...*take the necessary measures to ensure that when buildings undergo major renovation, the energy performance of the building or the renovated part thereof is upgraded in order to meet minimum energy performance requirements […] as this is technically, functionally and economically feasible...*».

This directive, and the one it has replaced, translated into national measures that imposed stricter and stricter performance standards for building technical elements — especially as regards those related to the building envelope — and actions to be undertaken in the design process, which can not anymore to take out of consideration, since the early design stages, the aspects related to the reduction of the carbon-based energy consumption, be it either in the framework of a new construction or a renovation. On the one hand, it is necessary to reduce the energy consumption of buildings to the minimum, without of course neglecting the architectural quality of the built space, through the adoption of novel, high-performing technologies as well as of environmentally and economically sustainable strategies; on the other hand, it is necessary to transform cities and buildings from simple consumer to producer of energy, generated on-site or nearby and in a clean way through the use of renewable energy sources.

With renewable energy is meant the energy that comes from resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat (Ellabban, 2014). The use of renewable energy sources is crucial not only for reasons related to environmental protection, it is also fundamental for other important social and political challenges: on one side, the *energy security*, related to the management of energy supply and the ability to meet future demand since, besides their ecological consequences, fossil fuels differently than renewable energy sources are, indeed, finite and they are not available everywhere in the planet; on the other side, the *energy equality*, dealing with the affordability and accessibility of energy for everyone[7].

Furthermore, in the European Directive on Renewable Energy Sources (RESD)[8], these latter are also acknowledged a strategic importance in «...*promoting technological development and innovation and providing opportunities for employment and regional development, especially in rural and isolated areas*...» (RESD, 2009).

Due to the all the above-mentioned reasons, the interest in renewable energy sources has grown in the last few decades. As a result, the investments in the sector increased: firstly, at research and development level, as witnessed by the great technological advancements occurred; at the industrial level, with a great increase in the market spread coupled with a significant decrease in the costs as well as the achievement of the so-called grid-parity in some countries; and at political level, resulting into incentivizing policies that boosted the spread of new installations of renewable energy plants all over the world. In the European Union, these policies have been the result of a common framework for the promotion of energy from renewable sources, established by the RESD by setting mandatory targets for Member States in terms of the minimum share of renewable energy sources, also in the light of the targets fixed for 2020. Within this framework, it should also be highlighted that renewable sources are also in line with a new decentralized energy distribution model, that is getting growing attention, especially in the EU[9]. Decentralized energy systems are distributed in the territory, characterized by smaller power capacities and typically use renewable energy sources. By contrast, conventional power stations (such as coal-fired, gas and nuclear powered plants as well as hydroelectric dams) are based on a centralized model, characterized by a large-scale power plant serving a large territory and often requiring energy to be transmitted over long distances. This results in distribution losses, that can become significant, on the way from the centralized generator to the final energy users. Moreover, other benefits related to the use of decentralized energy systems regard the utilization of local energy sources — also increasing the local security of the energy supply — and might also have social implications, such as the enhancement of «...*community development and cohesion by providing income sources and creating jobs locally...*» (RESD, 2009).

Besides all the above-mentioned considerations, it is also imporant to underline that the great potential of renewable energy technologies might lead them to exceed significantly the energy needs of the entire planet (Ellabban, 2014). This results perfectly illustrated in Figure 1.3. Finally, looking at the graph in Figure 1.4 that illustrates the global renewable-based power capacity additions by type and share of total capacity additions (IEA, 2015), the renewable energy sector has encountered a significant growth in the last 15 years and further improvements are expected in the future.

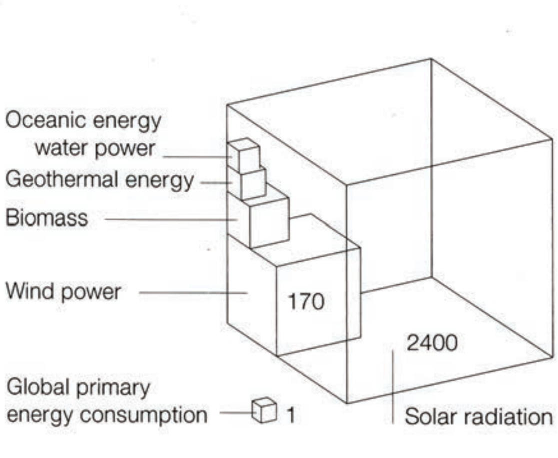


Figure 1.3 - Potential of renewable energy sources in relation to primary energy consumption (Weller et al. 2010)

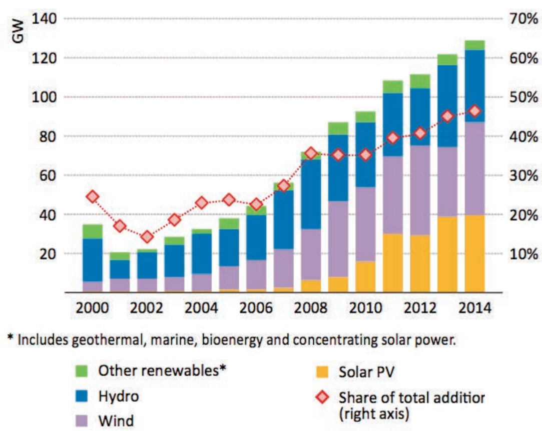


Figure 1.4 - Global renewable-based power capacity by type and share of total capacity addition (IEA, 2015)

1.2. Solar Energy in Buildings

Among renewable energy sources, the one deriving from the solar radiation on the earth's surface is undoubtedly the one with the greatest potential and the most available in nature (Figure 1.3). If the entire world population utilized effectively even to 0.04% of the available solar radiation, its worldwide energy needs would be fully satisfied (Weller et al. 2010).

Nevertheless, in spite of the great efforts carried out by the International community and the occurred advancements in this direction, fossil energy sources, finite and polluting, still remain the most largely used on our planet.

The concept of Solar Architecture indeed moved from this urgency to reduce non-renewable and fossil energy consumption and from the conscience of the great energy potential coming from nature and, in particular, from the sun. As Schittich underlined in its publication, indeed entitled *Solar Architecture* (2003), this concept gained importance in 1970s as a result of the two oil crises. In the same years, a more mature awareness regarding the environmental issues caused by humans' exploitation of natural resources emerged and terms such as sustainable development[10], energy efficiency and conservation started to become central in the contemporary debate not only at the technical-scientific level, but also in the field of architecture.

One of the most complete definition of what could be meant for Solar Architecture could be deducted from the *European Charter for Solar Energy in Architecture and Urban Planning*, drawn up by Thomas Herzog and signed in Berlin in 1996 by a group of over 30 among the most important European architects, from Renzo Piano to Norman Foster, from Alberto Campo Baeza to Richard Rogers...

Solar Architecture means designing buildings and urban spaces that guarantee the conservation of natural resources and make the best use possible of renewable energy sources, especially that — or better, those — coming from the sun. Solar Architecture has to do with the orientation of a building, with its exposure, morphology, climatic collocation etc., but also with the use of technical elements and building components that are able to take advantage of the inexhaustible amount of energy that everyday the sun places at our disposal. This latter, first of all, should be optimally captured — or either kept out — by the building envelope for the purposes of heating, cooling and natural illumination of indoor spaces in order to contribute to the achievement of adequate levels of thermal and visual comfort for building users. On the other hand, thanks to the technological progresses occurred, it can also be harvested and employed to power systems for the supply of electricity (Solar Photovoltaics - PV) as well as heating, domestic hot water (DWH) and, even, most recently, cooling (Solar Thermal - ST).

In the first case, it is possible to talk about *passive use of solar energy* in buildings; and in the second case, about *active use of solar energy*.

Before going into detail, with more comprehensive definitions and examples — that are provided in the next paragraphs — it is important to introduce another distinction, made in

Dassori & Morbiducci (2010), in order to separate the following three different scales of sustainable design principles[11]:

- *environmental principles* (princìpi ambientali);
- *typological principles* (princìpi tipologici);
- *principles of detail* (princìpi di dettaglio).

The first ones deal with the external environment where a building is designed and are based on the understanding and subsequent exploitation of environmental factors such as climate and related meteorological phenomena (temperature, humidity, solar radiation…), morphology of the site, local climate characteristics (e.g. soil, vegetation), etc.

The typological principles are linked more directly with the construction and correspond to the first overall design choices, which are directly — but, of course, not exclusively — influenced by the aforementioned environmental characteristics of the site: for example, the general orientation of the building must be carefully thought in relation to solar radiation, main wind directions, and site characteristics; the same applies to the shape of the building and, in particular, to its compactness (expressed by a ratio of the external surface by the volume) or either to the disposition of transparent surfaces as well as of indoor spaces, and so on…

Finally, the principles of detail regard the technical and technological solutions to be adopted for the actual construction of the building, in terms of both materials, building elements and constructive techniques. More in detail, these solutions mainly refer to the building envelope that is, indisputably, the most important subsystem with regard to the energy balance of buildings (Krippner, 2006). It indeed plays a central role in the design of energy efficient buildings, since it is the technical element fundamentally dedicated to the control and regulation of the energy fluxes between external and internal environments.

For the sake of clarity, the main focus of this thesis — as well as of the following dissertation about passive and active use of solar energy in buildings — is on the study of the technical and technological solutions (especially the most advanced) for the building envelope. Therefore, the discussion will not go in depth at the environmental and typological scales. These themes have been widely discussed in several works in the field of Sustainable Architecture, constituting important bases and/or references for this thesis, and are quite common and agreed design practices in the contemporary architectural panorama.

The main objective, in this chapter, is to introduce more in detail some of the terms and concepts that will be resumed later in this work and that could help understand the subsequent dissertations more easily, especially as regards passive and active solar technologies with specific focus on the building envelope.

1.2.1. Passive Solar Use

Resuming the definition given by Krippner (2006), passive use of solar energy «…*refers to the application of specific measures in the construction to collect, store and distribute incident solar energy, more or less without the implementation of technical devices*…» (p. 47). The building itself can make direct utilization of the energy coming from the sun — and, more in general, of natural resources — only by relying on its material properties, geometrical and constructional characteristics and by interacting by the surrounding environment. The environmental and typological principles — outlined in the previous paragraph — can definitely be included as examples in this field.

As Hegger (2003) highlighted, this is the simplest but, at the same time, the most effective form of Solar Architecture and, undoubtedly, it has deep roots into ancient architecture, which was ruled by a direct and spontaneous relationship between the built and natural environments. One may think about the ancient Greeks that oriented entire city grids toward the best exposures to maximize solar heat gain in coldest seasons[12]; or about Vitruvius, who in its famous treaty on Architecture underlined the importance of taking into consideration, in the architectural practice, the relation between climate context and architecture. For example, the *mashrabiya*, typical element of traditional Arabic architecture made by latticework wood, has been used since the Middle Ages to allow for solar protection and natural cooling during the hot summer seasons. Another example could be represented by the *windcatchers*, tower-like constructions, typical of ancient Persian architecture, used for activating natural ventilation in order to cool buildings and designed to maximize the so-called *stack effect*[13]. There are many lessons that can be learned from ancient architecture on clever passive use of the source of energy and light that is the sun[14]. In this sense, the sun can be used for both winter heating, summer cooling and daylighting, all aspects that deal, not only with the energy consumption of a building, but also with the wellbeing and health of people in buildings.

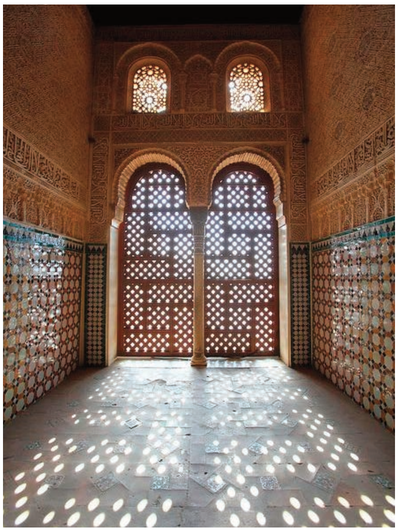


Photo 1 - Mashrabiya in Alahambra, Granada

Photo 2 - Picture of Windcatchers from Persian ancient architecture, Yazd, Asrabad, Iran

As regards the techniques for passive use of solar energy for winter heating, the **direct solar gain** coming through windows and glazing components has been since Romans' architecture the most widespread way to collect and store solar energy for improving indoor thermal comfort conditions in winter, while illuminating indoor spaces. At the same time, these components, which present a lower thermal resistance compared to opaque wall solutions leading to potential heat losses, might generate thermally discomfortable conditions especially during the nights.

The great developments of the last decades have made available a lot of new building materials, technologies, and (sub-)components for making the most of solar energy and daylight, while reducing heat losses to the minimum. For example, vacuum insulation in the cavity/ies of multiple glazing units allowed for the achievement of very high insulation performance, with reduced thicknesses and without affecting the solar transmission of the glazing: a technique that moved from space applications to architecture. Special coatings have been developed to reduce heat losses and improve thermal insulation of glazing systems from the inside to the outside of buildings[15].

In addition, the infills of windows and façade systems can also be integrated, in the form of sheets and blocks, with so-called **Transparent Insulating Materials (TIM)**, such as Aerogels. These latter (that in actual facts are translucent) can be used to improve the thermal performance of windows and façade systems, while at the same time letting some daylight enter the building. Due to their solid and yet extremely lightweight nature, deriving from a open porous structure made almost entirely of air, aerogels — and, in particular, silica gel based ones — have found a great application in the most diversified sectors, but thanks to their remarkably low thermal conductivity, their most substantial impact has indeed been for the realization of highly-insulating products for the construction and industrial insulation sectors (Koebel et al. 2012). Speaking more in detail of their use in buildings, they represent something more than translu-

Photo 3 - Polycarbonate panels with aerogel insulation: School Gymnasium, Pbr Planungsbüro Rohling, Mainz

Photo 4 - Trombe-Michel wall installed in the retrofit of residential complex in Piazzale Moroni, Savona, 2003-2012 cent, super-insulating materials: when solar energy pass through them, they heat up and act as solar heating systems; moreover, if coupled with a good thermal storage capacity, they might also maintain thermal comfort also during winter nights and overcast days (Hegger, 2003).

The use of thermal storage masses, enabling for a delayed transmission of heat into the interior of a building and thus helping to maintain almost constant indoor temperatures regardless of the outdoor thermal fluctuations, is one of the most ancient principles of passive use of solar energy in buildings for the satisfaction of both heating and cooling requirements and, nowadays, is at the base of several sustainable building concepts[16]. However, the advancement related also to the use of aerogels have enabled to reduce the thickness and weight of these thermal storage elements and, moreover, to make them translucent: in this regard, Beatens et al. (2011) highlighted how the possibility to achieve high transmittance in the solar spectrum is of high interest in the construction sector and, at the same time, how the light-scattering properties of aerogels can be exploited for the attainment of evenly distributed daylight illumination in interior spaces, still with very good thermal insulation performance.

This field of solutions, where the solar radiation is collected, stored, and then distributed by using appropriate thermal storage materials and/or building elements, can be referred to as indirect gain, according to the definition provided in DOE, 2012. Another solution that can be listed in this field is the so-called **"solar wall"**. This system is characterized by at least the following elements: a supporting structure providing high thermal absorption and storage capacity; an air cavity of varying thickness right in front of the supporting layer, connected to both indoor and outdoor spaces by means of air vents; a front glass that, taking advantage of the greenhouse effect[17], heats up the air in the cavity and the supporting structure. This glazed cladding element might also be shaded, when necessary and, in particular, in warmer seasons, in order to prevent from the overheating of the wall. This peculiar type of solar wall is known as **"Trombe-Michel wall"**[18]. In Figure 1.5 is reported the functioning of

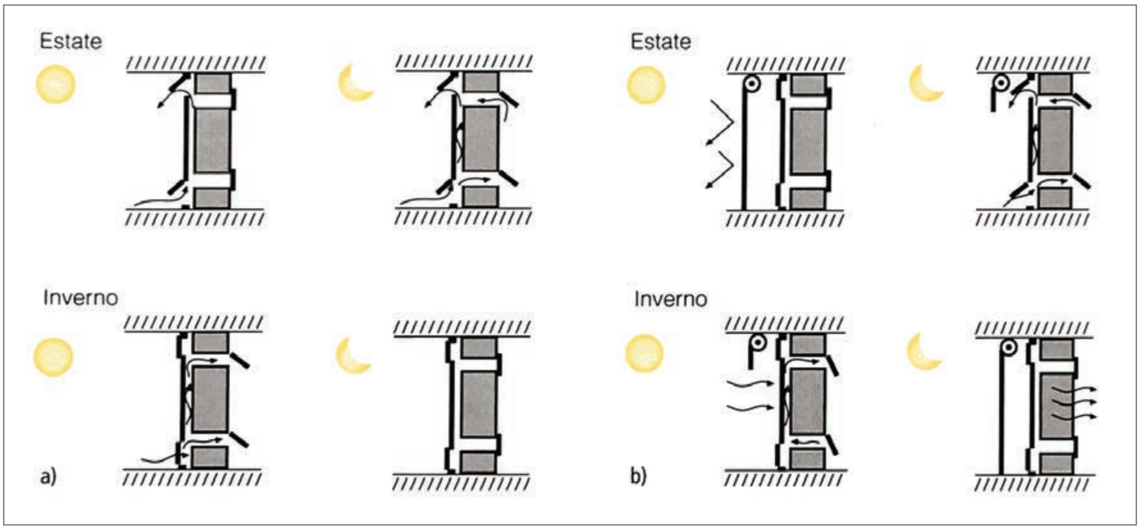


Figure 1.5 - Functioning Scheme of a Solar Wall (Dassori & Morbiducci, 2010)

these passive solar solutions, according to the seasons and the time of the day. During winter days, in particular, the heated air flows inside the building through the vents predisposed into the supporting structure, while this latter collects and stores heat from the sun to be released later in the night. Conversely, in summer, front glass can be opened to let the warm air flow out of the building.

Similarly, also the so-called **"double-leaf" or "double-skin" façades**, widely used especially in contemporary high-rise buildings, are able to respond to outdoor climate conditions and satisfy indoor comfort requirements. These are characterized by two glazed surfaces, separated by a large internal cavity (with thicknesses ranging from 20-30 cm to over 100 cm) and fixed to the load-bearing structure of the building. Inside the cavity, air coming from internal and/or external environments, is let flow and used to regulate and optimize the temperature, humidity and daylighting inside the building. In double-leaf façades, natural ventilation systems can often be "supported" by mechanical ones (for which we can not really talk about passive solar technique). However, these technical building solutions are based on the exploitation of "natural" phenomena — i.e. the stack and greenhouse effect and their ability to induce free natural ventilation mechanisms — as well as of material properties — i.e. the transparency of the constituting glass surfaces — in order to maximize the comfort levels inside the building, through the provision of both heating, cooling and daylighting. In this perspective, they can definitely be considered among the examples of passive solar energy utilization. A comprehensive review of double-skin façade solutions is provided in Poirazis, 2006.

The so-called **"sun spaces"**, which recur in several of the case studies presented later on in this work, are based on similar considerations of natural resources and, also in this case, the greenhouse can be individuated as the main reference.

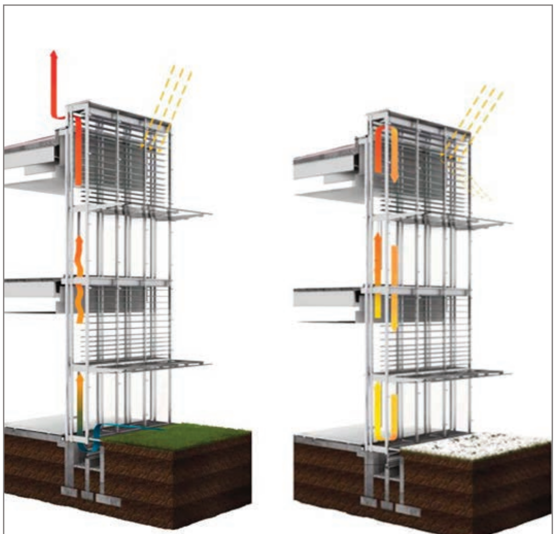


Figure 1.6 - Double-skin façades: two possible winter and summer functioning schemes (Regazzoli, 2014)

Photo 5 - Intesa San Paolo Tower, RPBW, Turin, 2014 *(top)* Inside view of double-skin façade; *(bottom)* outside view

The sun spaces — also referred to as winter gardens or either glazed buffer zones — are generally located on the south-exposed surface of the building and are actually used as solar energy storage systems[19]. In winter, the heat collected in such spaces is convected towards the inner spaces, helping to increase their temperature without the need of any technical devices; they can also be provided of elements with high heat storage capacity in order to further increase the passive solar heating potential. Besides this winter heating capability, which makes this solution particularly widespread and indicated for colder Northern countries, it is also provided of openings for natural ventilation, positioned strategically in order to make it adaptable to seasonal changes: so, during summer, a sun space can be opened, in order to allow for natural cooling, and protected from solar radiation, by means of shading/obscuring elements, transforming this space into a potential semi-open additional livable space in a building. In this regard, Hegger (2003) actually states that these spaces «…*make sense in the perspective of energy efficiency only if they are unheated and not intended for everyday use*…» (p. 21), underlining how the large glazed surface cladding the building might be a problem in terms of thermal comfort, due to rapid cooling in winter nights and overheating in summer days. A correct design and dimensioning of the sun space and a careful choice of the properties of the components of the building envelope (in terms of thermal insulation, air-tightness, solar shading performance, etc.) and of ventilation mechanisms might actually optimize and extend the livability of these spaces, without requiring any artificial system for achieving thermal comfort.

Sun spaces are particularly used in northern latitudes in the field of the energy retrofit of collective residential dwellings, where they are obtained by cladding in glazing (and often expanding) the existing south-facing balconies. This way, new spaces able to collect, store and distribute solar energy are generated, houses energy requirements are reduced[20], quality of life is improved and, last but not least, a reconfiguration of the façade of the buildings is possible[21] (Photo 6, 7).

Photo 6 - Det Gule Hus, Esbensen Engineering, Aalborg, 2000: retrofitted façade with PV-integrated sun spaces

Photo 7 - Sun spaces added in the renovation of Tour Bois-le-Prêtre, Druot Lacaton and Vassal, Paris, 2012

Several of the above-cited passive solar techniques can be adaptable to provide both winter heating and summer cooling and we have seen how the exploitation of solar energy to generate diversified ventilation flows can help optimize thermal indoor comfort conditions, both in colder and warmer times of the year. The use of sun-shading devices as functional layers of transparent windows and façades, skylights and roofs as well as openings is a measure for improving almost exclusively summer thermal comfort, by reducing the solar heat gain across the building envelope. However, besides this aspect, sun-shading devices have a fundamental role in the optimization of visual comfort conditions, since they have a direct effect on light transmission across the building envelope. Studying the most appropriate configuration of sun-shading devices in terms of shape, orientation, materials, and characteristics is an important aspect for the attainment of visual comfort condition on the interior of buildings, which turns out of even greater relevance especially in work spaces[22].

1.2.2. Active Solar Use

Active use of solar energy «…*refers to additional technical measures for absorbing, distributing and, if necessary, storing solar energy; i.e. collector technology and heat pumps employed to complement heating and cooling measures, as well as photovoltaics and wind energy as power generators*…» (Krippner, 2006, p. 47).

Differently than passive technologies and techniques, which, in many cases, have a long history of applications and do not really bring new elements in the building envelope (Munari Probst & Roecker, 2012), with active solar technologies, more complex integration issues arise and competences coming from different fields (e.g. plant design) are required. These technologies must indeed interact with the technical systems of the building, without compromising the architectural space. New elements are introduced into the building design: for example, in the case of PV, the solar modules for the energy collection and conversion into electricity, along with all related components (electrical components, cables, inverters, storage systems, etc.).

Here, in particular, the main focus is on the technologies for renewable energy generation from the sun: namely, Photovoltaics (PV), Solar Thermal (ST), and hybrid solar technologies (PV/T).

1.2.2.1. Solar Thermal (ST)

In paragraph 1.2.1. several more or less sophisticated ways of passively, i.e. without the need of specific technical devices, collecting and distributing solar thermal energy have been listed. However, this latter can also be actively harnessed by means of surfaces optimized for heat collection (absorbers) and then transported into the building, by means of a fluid carrier medium (air or water).

This whole system, either used for space and water heating, is referred to as "solar collector", which is the basic component of active Solar Thermal (ST) installations.

Based on the carrier medium utilized for the transportation of the collected solar thermal energy (water or air), it is possible to distinguish two main families of ST collectors, *Air systems* and *Hydraulic systems:*

- *Air systems* are characterized by lower costs, but also by lower efficiency and storage capacity compared to hydraulic ones, due to the limited thermal capacity of air with respect to water;
- *Hydraulic systems* are characterized by the greatest energy-saving potential and, thus, they are also the most widespread systems for active solar thermal energy collection in buildings.

Hydraulic systems can be in turn subdivided into three main technologies, characterized by different performance and, subsequently, different uses:

- Unglazed flat-plate collectors, also referred to as solar absorbers (Figure 1.7);
- Glazed flat-plate collectors (Figure 1.8);
- Evacuated tube collectors (Figure 1.9);

The basic functioning principles of these three technologies is similar. In all cases, the following functional elements are present: a solar absorber, typically made of a thin metal sheet (usually in copper) often with a selective coating able to maximize the energy absorption, while minimizing heat radiation losses; a hydraulic system, directly in contact with the absorber, for the transportation of the collected heat through water; a rear insulation layer, used to reduce heat losses and optimize the efficiency of heat collection.

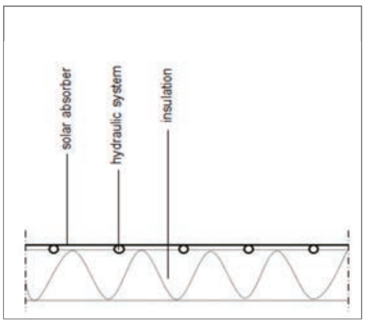


Photo 8 - Example of roof-mounted unglazed flat-plate ST collector; Figure 1.7 - Typical cross section with indication of main components (Munari Probst & Roecker, 2012)

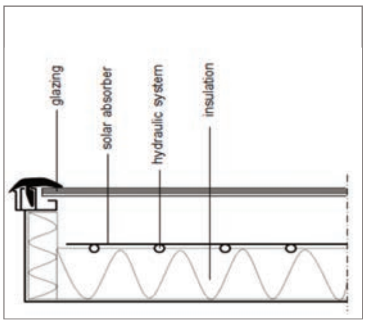


Photo 9 - Example of roof-mounted glazed flat-plate ST collector; Figure 1.8 - Typical cross section with indication of main components (Munari Probst & Roecker, 2012)

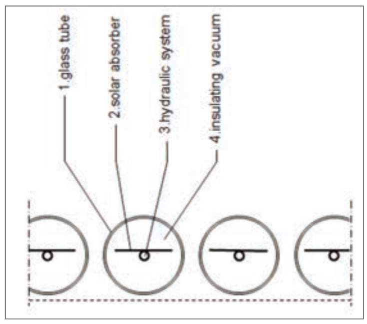


Photo 10 - Example of roof-mounted evacuated tube ST collector; Figure 1.9 - Typical cross section with indication of main components (Munari Probst & Roecker, 2012)

The unglazed flat plate collector is the simplest form of collector as well as the least expensive; however, at the same time, this technology is also the least performing, due to the absence of the front (and, sometimes, also of the rear) insulation. This obviously translates into higher heat losses as well as lower heat collection and storage. For these reasons, its use is most spread, for example, for direct water heating for open-air swimming pools, which are almost exclusively utilized in the warmest periods of the year and where heating requirements and radiation supplies usually overlap (Krippner, 2006). They can also be used in case of low space heating requirements and DHW pre-heating (Munari Probst & Roecker, 2012). For the solar absorber, a less expensive and performing polymeric material can be used instead of thin metal sheets, depending on the level of efficiency required for the system.

Glazed flat plate collectors are characterized by the largest spread in EU, for both space heating and DHW production (Munari Probst & Roecker, 2012). They are characterized by a more complex structure, consisting of a rectangular shape with a thickness of around 100 mm. The addition of a covering glass, slightly distanced from the absorber layer, allows for the creation of an insulating air cavity. This latter reduces heat losses and guarantees a more efficient performance.

In the evacuated tube collectors, the vacuum that is created around the absorber allows for a significant reduction of all the heat losses and leads to the highest operating temperatures and efficiencies. This technology, in particular, is constituted by a series of glass tubes interconnected into larger panels by means of a connector box, leading to a modular conformation. It is the most expensive among solar thermal technologies, but also the best performing since, thanks to the vacuum insulation, losses are kept to the minimum, even in colder climates, and the operating temperatures can reach 180 °C. For these reasons, as Munari Probst & Roecker underlined, they are recommended for applications requiring high operating temperatures, such as solar cooling and industrial application, but also for space heating and DHW production, especially in cold climates.

The use of Solar Thermal technologies in the building stock, for both DHW preparation and space heating, is gaining a growing attention. Several efforts are also exploring the potential for Building-Integrated Solar Thermal (BIST). Some examples are shown in Photos 11-13.

Photo 11 - Flat-plate glazed collectors integrated in the façade of Kraftwerk B, Bennau, Grab architekten, 2009

Photo 12 - Evacuated tubes as façade elements of Social housing in Rue de la Cabonniére, Philippon-Kalt, Paris, 2010

Photo 13 - Evacuated tubes installed as balcony parapets at Sunny Woods, Beat Kämpfen, Zurich, 2001

1.2.2.2. Photovoltaics (PV)

The word Photovoltaics (PV) was created to describe the basic principle underlying the functioning of a solar cell, i.e. the conversion of light (from ancient Greek, *phós*) into electricity (from the name of Alessandro Volta, the inventor of the electrical battery).

Although the discovery of the *photovoltaic effect* occurred in 1839, due to the French physicist Alexandre Edmond Becquerel, it is necessary to wait until the half of 20th century to begin to see the real potential of application of this technology, with the first applications in the aerospace sector.

From the first civil installations of PV modules in the 1970s until today, photovoltaics has been constantly growing at exponential rates and is now supplying around 1% of global electricity production and 7.9% of the Italian electricity production, the highest share among all countries in the world (IEA-PVPS, 2014).

Thanks to the great investments put in place in this sector, module performance have increased and prices have dropped remarkably especially in the last decade. As a result, the predictions for future growth seem to be promising as well[24].

Three different generations of PV technologies can be identified: the first generation, representing today around 90% of the PV market, is based on the use of crystalline silicon; the second generation, aimed at the optimization of materials, is most commonly known as thin-film photovoltaics and is indeed based on films of micrometrical thicknesses of semiconductor materials; the third generation — generally indicated as "organic-based" or, more simply, "organic" PV due to the origin of basic components — is based on the use of nanotechnology and nano-materials. It is trying to give answers to the new requirements expressed by the PV market (flexibility, lightness, cost-effectiveness, versatility).

Within this general framework, a wide variety of PV technologies have been developed[25], but only some of these have reached or have the potential to reach a large-scale commercial deployment.

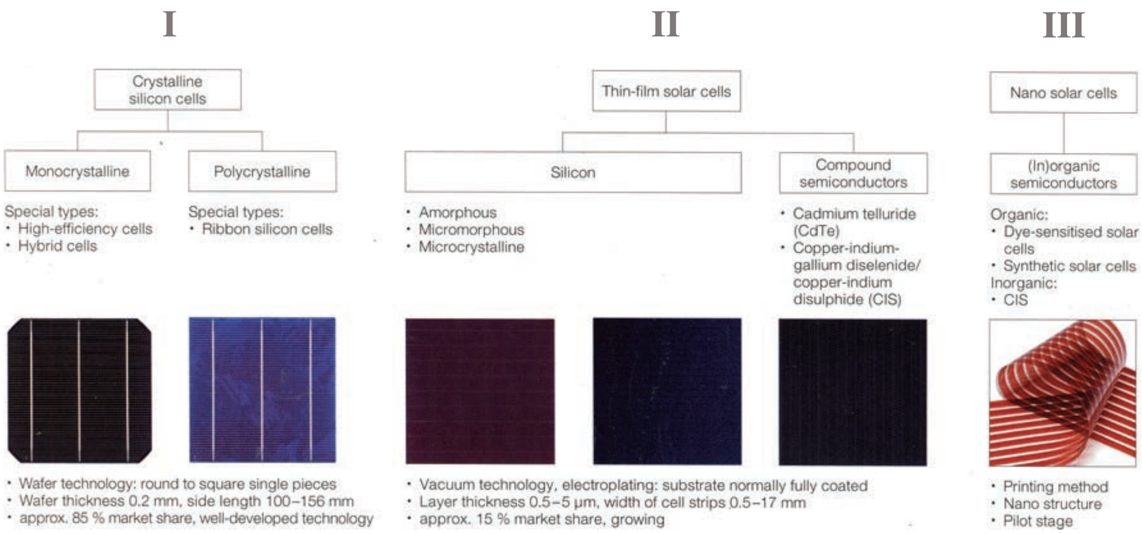


Figure 1.10 - The three photovoltaic generations (Weller et al. 2010)

1.2.2.3. Hybrid Solar Photovoltaic and Thermal (PV/T)

Before going more into detail with the description of the photovoltaic technology, it is worth to cite the existence of a branch of research and development dedicated to hybrid systems that combine it with components for solar thermal production. These systems, briefly referred to as PVT (Photovoltaic Thermal), can either be based on water or air medium and this leads to a great variety of possible solutions, related technical issues and performance. A comprehensive review of this type of systems is provided in Chow et al. (2010), where it is possible to find a detailed description of the great variety of solutions that have been designed, analyzed numerically and tested experimentally in this field. The basic concept moves from the idea of exploiting a stream of air or water to cool-off the PV modules — thus, improving their operating performance of electricity production — and reuse the heat extracted by the coolant to power solar thermal applications as well. This has also interesting potential for building-mounted installations: as Chow (2010) indeed underlined, PVT might provide higher architectural "uniformity" at the building level, instead of placing two separate arrays, each with their own aesthetic appearance and characteristics. Nevertheless, in spite of the research efforts in designing and understanding their thermal and electrical performance and of their great potential for cogeneration in the built environment, commercially available PVT systems remain still quite limited due to barriers in terms of cost and reliability.

1.3. The Photovoltaic Technology

A more comprehensive study of the PV technology, which is the main focus of this work, is the object of this paragraph, where main performance indicators are introduced, the factors affecting the operating behavior of solar modules are discussed and a quick overview of the PV-related components is provided.

1.3.1. Parameters for the Assessment of the Photovoltaic Performance

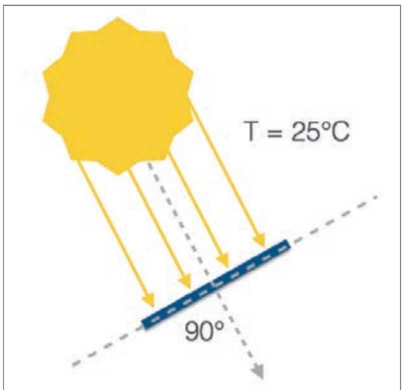
The main parameter for the qualification of a PV cell performance is the Nominal Conversion Efficiency (η), measured in Standard Test Conditions - STC (Figure 1.11) and defined by the following formula:

$$\eta = \frac{P_p}{A \cdot I_{STC}} \qquad [1]$$

where:

- P_p is the nominal (or peak) power of the cell, expressed in Watt-peak (W_p);
- I_{STC} is the solar irradiance at STC (equal to 1000 W/m^2);
- A is the sun-exposed surface of the cell (m^2).

A module is a unit obtained by connecting, either in series or in parallel, a certain number of solar cells; in turn, modules can be combined with other modules to form panels[26].



Standard Test Conditions (STC):
- Temperature: 25 °C;
- Solar Spectrum: AM 1.5 G;
- Solar Irradiance: 1000 W/m^2;
- Direct Irradiation, normal to the cell

Figure 1.11 - Standard Test Conditions

The efficiency value of a module is always some points lower than that of the single cells. This is mainly due to the spaces between one cell and the other, not allowing for the whole module surface to take part in the PV conversion, but also to the presence of interconnections, often in front of the active layer. In addition, other causes might be imputable to connections losses and more or less present defects in modules.

Actually, evaluating the efficiency in relation to the whole module area surface — and thus accounting for both the active area and the inactive parts, involving e.g. connections and frames — is a commonly used simplification that enables to associate the power of the system to the area effectively occupied by it.

In particular, the ratio of the power available from a photovoltaic system per unit area can be indicated as *photovoltaic power density*, expressed in W/m^2, and is a very useful parameter to compare different solar products, rather than different technologies, for which the conversion efficiency still remains the most common reference parameter. Directly linked with the power density, another parameter useful for the comparison of different PV products and that will be referred to in the course of this work, is the so-called *space requirement*. This latter is the surface (m^2) needed to obtain a certain amount of installed power, generally 1 kWp[27].

1.3.2. Real Operating Performance of PV modules

The nominal conversion efficiency is defined in standard conditions, reproduced in laboratory and referring to an instantaneous situation that basically never occurs during actual operations (and that is also particularly favorable for first-generation technologies). It is a useful reference for the comparison of different PV technologies, but in order to understand the actual energy production of PV modules, it is important to consider what occurs in real operating conditions. This means evaluating the influence on energy production performance of a series of aspects, such as: the variation in the temperature of the devices, the geographical localization of the PV plant, the angle of incidence as well as the “nature” of the incident solar radiation. The various photovoltaic technologies react in diversified ways to these aspects, with obvious consequences on the actual energy generated over a certain time (expressed in kWh) when a PV system of a given power (kWp) is installed. Considering these aspects is fundamental for the choice of a PV technology or another.

First of all, an increase in the **temperature of the solar cells** compared to the 25 °C of STC generally implies a drop in the performance of PV modules. This must be considered carefully, especially in warmest and sunniest contexts, where temperatures of modules might also increase up to very high temperatures (such as, for example, 80 °C), but in general it is an issue in most of the cases, since the 25°C temperature is easily overcome in operating conditions due to solar absorption. De facto, only a certain percentage (that is expressed by the efficiency of the solar device, hardly ever overcoming 20%) of the incident solar energy absorbed by the modules is converted into electricity, through the photovoltaic effect. The remaining part, deducted the reflected portion, is converted into heat (also referred to as “conversion heat”) that provokes an increase in the temperature of PV devices. Thus, in order to express the behaviour of a PV module in relation to the operating temperatures, the reference standards for PV modules performance qualification define the so-called *temperature coefficients*, expressing the drop of PV module performance for each 1°C increase in modules temperature[28]. The temperature performance varies according to the type of semiconductor used: for example, the power of crystalline silicon solar cells drops of 0.40-0.50% for each 1°C increase in modules temperature, whereas amorphous silicon has a 0.20%/°C temperature coefficient. Thus, especially in the first case, a rear ventilation of the PV devices is highly recommended, in order to avoid excessive power losses as well as thermal stresses on the solar modules.

Another aspect that influences the energy production of a PV systems is obviously correlated to the amount of solar energy that strikes it during operation. This amount depends on several factors: firstly, the **geographical location** of the PV system. Besides the already introduced considerations related to temperatures, different sites of installations are indeed characterized by different climatic conditions (hours of sunshine, of cloudiness, of rain, and so on...) and sun paths. Those aspects have a significant influence on the output power and must be carefully considered when designing a PV installation. If we look at Italy, for example, the average yearly solar irradiation on a horizontal plan (GHI, Global Horizontal Irradiation) differs remarkably from north to south and, in particular, it ranges from 1,000 to 1,850 kWh per square meter[29], whereas the productivity of a 1 kWp plant goes from 900 to 1,500 kWh[30].

Another aspect that influences directly the amount of incident solar energy on PV systems — and thus their energy production performance — is their **orientation**, which is described by means of two main parameters, illustrated in Figure 1.12:

- *tilt* (a_1) that is the angle between the solar panel and the horizontal plan;
- *azimuth* (a_2) that is the angle between the south direction and the projection on a horizontal plan of the normal (n) to the solar panel surface.

In the northern emisphere, the direct solar irradiation is maximum when the photovoltaic surface is oriented towards south (a_2=0°). The tilt (a_1), i.e. the inclination with respect to the horizontal, varies with the latitude (e.g., in Southern Europe is approximately 30°). The latitude, indeed, is directly related to the path of the sun and with its inclination with respect to the earth surface, changing slightly from one place to another.

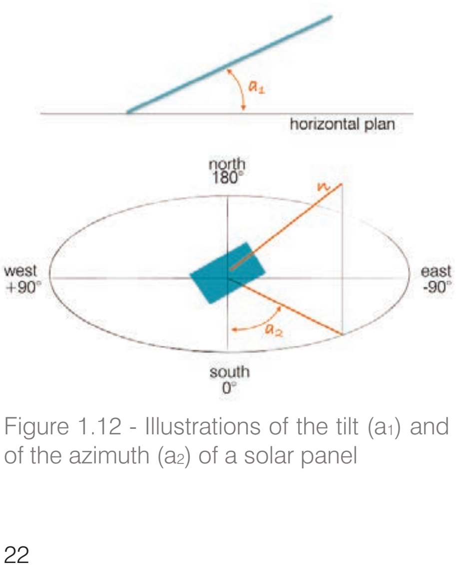


Figure 1.12 - Illustrations of the tilt (a_1) and of the azimuth (a_2) of a solar panel

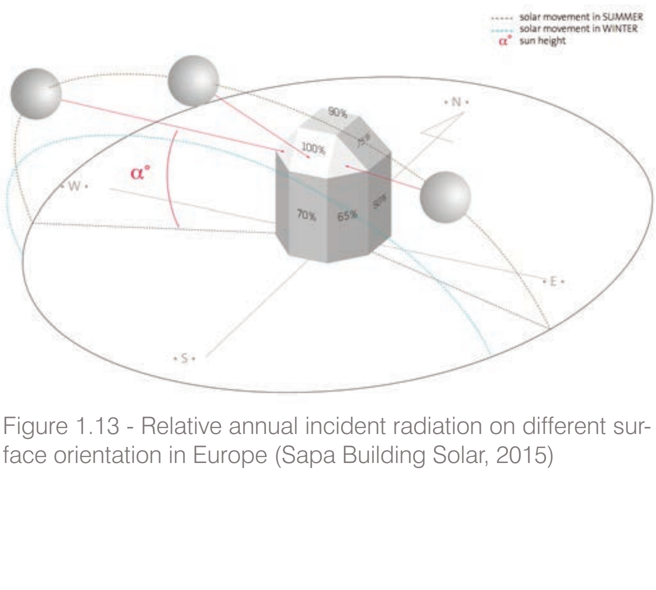


Figure 1.13 - Relative annual incident radiation on different surface orientation in Europe (Sapa Building Solar, 2015)

When the orientation changes from this "optimal" position, the percentage of direct solar radiation that strikes the surface of the PV modules decreases, with a subsequent drop in the energy production. For example, in Figure 1.13 is shown that, when solar modules are laid horizontally (tilt, $a_1=0°$), a 10% reduction of the direct solar radiation occurs, independently of the azimuth (a_2); whereas, moving to vertical surfaces, a more important drop in the direct solar radiation occurs, equal to 30% in south-oriented surfaces ($a_2=0°$) and to 50%, in east- and west-oriented surfaces ($a_2=\pm 90°$). On north-exposed vertical surfaces, this value further drops to 70% and solar cells functioning mainly depends on reflected and/or diffuse light. In this regard, it is important to underline that solar cells can function with both direct, diffuse and reflected light, however direct light is the richest in energy. In sunny days, where there are no clouds in the sky, it is possible to obtain the peak values of solar radiation (1000 W/m^2, as in the STC). However, in some days, the incident sunlight on solar panels might not even reach 50 W/m^2 (a value even be comparable to artificial lighting). Each PV technology presents different responses to the various irradiation conditions, as will be widely discussed in the following chapter: in order to characterize this response, the reference standards for PV modules qualification (IEC 61215:2005 and IEC 61646:2008) prescribe a test for the definition of solar modules performance at low irradiance (200 W/m^2).

Finally, another very important aspect that must be considered when designing a PV installation, directly linked with the amount of solar energy harvested, is the **possible shading of the modules** due to, e.g., dirt, dust, snow, vegetation. Even a partial shading might cause great losses, especially in arrays of modules connected in series, where a single module can affect the whole system performance.

Once all these aspects are known, it is possible to make an estimation of the productivity of the PV system, given a certain area and power installed, or vice versa to dimension a system based on a specifically required energy production. This can be done either with the support of dedicated software specifically developed for annual solar simulations[31] or by using analytical formulae, such as the following, resumed from Munari Probst & Roecker (2012):

$$E = GHI \cdot OF \cdot A \cdot \eta \cdot c \qquad [2]$$

where:

- *E (kWh/year)* is the yearly energy production of the systems;
- *GHI (kWh/m² year)* is the *Global Horizontal Irradiation*;
- *OF (%)* is the *Orientation Factor*, ranging from 30% to 100% and taking into account the percentage loss due to angles of installation (tilt and azimuth) that do not coincide with the more advantaged ones (they are reported in Figure 1.13);
- *A (m²)* is the area of the PV system;
- *c (%)* is a *correction factor* accounting for the possible losses due to temperature effect (more or less accentuated in relation to the presence or absence of rear ventilation), shading on modules, electrical issues, etc. It also depends on the PV technology and on its response to particular operating conditions: typically, in crystalline silicon modules, *c* is set to 75%.

In the field of this discussion, it is worth to mention the development of so-called "sun-tracking" systems, aimed at the maximization of direct solar irradiation. Due to the relative motion of the earth with respect to the sun, it is impossible to put solar panels in a fixed position able to realize, in all cases, the best irradiation conditions: in response to that, these movable systems are designed to rotate in order to "track" the sun. They can be single- and double-axis, thus rotating in one or two directions respectively. Being based on the use of motors and sensors, sun-tracking PV plants are more expensive and complex than fixed ones, but obviously characterized by higher yields: the higher construction, maintenance and management costs should be compensated by the value of the surplus energy generated.

1.3.3. Photovoltaic System and Related Components

Modules and panels present very low current and voltage values, so they need to be connected either in series and/or in parallel in order to reach values relevant to the electric loads to be supplied. Besides these and the related supporting structures, other components are needed for a photovoltaic system to function. First of all, at least one inverter is needed to transform the variable Direct Current (DC) provided by the PV panels into Alternating Current (AC) that can be injected into the electrical grid (Grid-connected system) or used by a local, off-grid electrical network (Stand-alone system). Another task that the inverter is called to perform is the maximum-power-point tracking, in order to make the system work with the best current/voltage combination (Di Dio et al., 2010).

According to the dimensions and the characteristics of the system, it is possible to opt for more conventional string inverters that are connected to several solar panels or either smaller inverters, called micro-inverters, converting the DC current provided by one single solar module into AC. Micro-inverters, which have only recently started to spread, help avoid that the failure of one module or also its partial shading lead to a disproportioned reduction of the entire PV array. A related disadvantage is linked to the higher initial as well as maintenance costs compared to a more conventional central inverter, an aspect that is pushing some PV manufacturers towards the development and commercialization of panels with built-in micro-inverters. The DC/AC inverters represent fundamental components of a photovoltaic system and, in particular, of the so-called "Balance of System" (BOS) — i.e. all components of a photovoltaic system other than the photovoltaic panels — encompassing wiring, switches, mounting system, control and metering devices, batteries, etc. Storing the electricity is very important in PV, especially in stand-alone systems, considering the fact that the peak in the electricity production hardly coincides with the peak in the energy requirements. In grid-connected systems, the energy produced is virtually stored in the local electrical grid.

Although such aspects involve more closely the competences of plant designers and installers, it is important that, for building-mounted installations, building planners account for these components, not only because they are physical objects requiring dedicated space in buildings, but also because they have a relevant incidence on the cost of a solar installation, ranging from 40-60% of the total system cost (Munari Probst & Roecker, 2012)

Notes

1) Taken from the Article 2 of The United Nations Framework Convention on Climate Change (UNFCCC), international environmental treaty negotiated at the United Nations Conference on Environment and Development (UNCED), best known as the Earth Summit, Rio de Janeiro, June 1992.
As of March 2014, UNFCCC has 196 parties that meet regularly for the so-called Conference of the Parties (COPs), where important progresses, goals and directions in the fight to climate change are discussed. One of the most important COPs, held in 2010, in Cancùn (Mexico), established future global warming should be limited to below 2.0 °C compared to the pre-industrial level.

2) Also known as Intended Nationally Determined Contributions (INDCs)

3) Recast in 2010, it amends and modifies the former directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.

4) A more comprehensive review of the definitions and calculation methodologies of Zero-Energy Buildings (ZEBs) is provided in Marszal et al. 2011.

5) The energy performance of a building is defined in the EPBD and it depends on the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use, also taking into account the heating and cooling energy requirements to maintain the comfort temperature conditions of the building, as well as domestic hot water needs.

6) Article 9, EPBD, 2010.

7) Cf. RSC - Royal Society of Chemistry, Energy. Supporting the chemical science community to help create a sustainable energy future, Retrieved from www.rsc.org/campaigning-outreach/global-challenges/energy/#solar.

8) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

9) «...*It is appropriate to support the demonstration and commercialisation phase of decentralised renewable energy technologies...*» (RESD, 2009).

10) The most famous definition of Sustainable Development can be taken from the so-called "Brundtland Report": «...*Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs...*». Cf. WCED - World Commission on Environment and Development (1987), Report of the World Commission on Environment and Development: Our Common Future, also known as Brundtland Report from the name of the Chairman of the WCED, Gro Harlem Brundtland (Norwegian Prime Minister, at that time).

11) Which, more or less directly, correspond to just as much stages in the design process.

12) Cf. http://webecoist.momtastic.com/2009/01/25/ancient-green-architecture-alternative-energy-design.

13) With stack effect (also known as chimney effect) is meant the movement of air in and out of buildings, resulting from air buoyancy, due to a difference in indoor-to-outdoor air density linked with temperature and moisture differences. In particular, equal the volume, warm air has a lower weight compared to cold air, therefore it tends to move upwards, activating convective air flows. The greater the thermal difference and the height of the structure, the greater the buoyancy force, and thus the stack effect. This bioclimatic effect, exploiting solar radiation and wind directions, has been widely used in ancient architecture to activate natural ventilation mechanisms, especially in warm and arid climate areas, where the warmest air coming from south-exposed surfaces was usually also cooled-down by means of water basins.

14) In several works, those have been treated extensively, in general or by focusing on the different geographical areas, which lead to completely different technical solutions for making the most of natural resources. To name a few, Hegger (2003), DOE (2014).
15) For a significantly comprehensive review, regarding the state-of-the-art and the possible evolution of fenestration system technologies, please refer to Jelle et al. (2012).
16) Consider, for instance, solutions such as green roofs, roof ponds, etc.
17) Greenhouse effect is the effect based on which greenhouses function and become warmer under the sunlight: glass lets the solar radiation get inside the building, this radiation is then absorbed by all the elements inside the greenhouse and subsequently reemitted as heat in the form of far IR radiation that glass is not able to transmit. Since, in the greenhouses, this heat is prevented from leaving the structure through convection, their internal temperatures increase significantly.
18) Developed in the 1960s, by Felix Trombe and Jacques Michel in France, which have prototyped and tested this system, patented in 1881 by Edward Morse.
19) After having defined direct and indirect gains as possible categories into which subdivide passive solar heating techniques, DOE (2012) talk, in this case, about isolated gain, referring to the possibility to collect solar radiation in an area that can be selectively closed off or opened to the rest of the house.
20) Amounting, in the most basic solutions, to around 10-20 kWh/m^2 year for each apartment (Gallo, 2010).
21) In some of the case-studies analyzed in this work and in many of the built examples of architecturally integrated PV studied during its elaboration, the construction of sun spaces in the field of energy retrofit of existing buildings have offered the availability of surfaces as well as the appropriate location to integrate PV products.
22) For example, as a general rule, horizontal (more or less tilted) sun-shading devices are most advised in south orientations, whereas on east and west sides vertical sun-shading is most appropriate. The movability of sun-shading elements is a suggested feature in order for them to optimally adapt to ever-changing position of the sun as well as building and occupants' requirements; however, making these elements movable might increase their economic cost, especially in case of self-activating devices, which also require higher operation costs and, therefore, lead to prefer less costly and "easier" to manage fixed solutions. The best balance in terms of cost, performance, and building requirements should be assessed in the design phase by using softwares for building energy simulation.
23) Besides the advantages related to the ease of maintenance and substitution of elements (fundamental especially with regard to the fact that the upkeep of vacuum is actually a very difficult task), this has a certain potential also in terms of building integration.
24) For more details, cf. en.wikipedia.org/wiki/Growth_of_photovoltaics#cite_note-iea-pvps-snapshot-1992-2014-3.
25) A complete e regularly updated of the evolution of the research in the field of PV is provided by the "Research Cell Efficiency Records" chart, maintained by National Center for Photovoltaics (NCPV) of the National Renewable Energy Laboratory (NREL), http://www.nrel.gov/ncpv/
26) It is worth to underline that, although they are often referred to as the same object a panel is a group of modules, preassembled, fixed together mechanically and connected electrically.
27) An aspect that, for obvious reasons, is fundamental in the field of building integration of PV (which is the main object of this work).
28) The standards IEC 61215 and IEC 61646 establish three temperature coefficients: the first (α) is related to the short-circuit current I_{SC} ot the PV module; the second (β) to the open-circuit voltage, V_{OC}; the third (δ) to the

maximum power P_{MAX}. The three are obtained experimentally from module measurements, according to the procedures described in the standard.

29) Cf. www.solarGIS.info.

30) Cf. http://re.jrc.ec.europa.eu/pvgis.

31) Several softwares can be used for this purpose such as PVGIS (developed by the Joint Research Center of the European Commission and available at http://re.jrc.ec.europa.eu/pvgis) or SunSim (www.sunsim.it). This latter is used in the calculations on the case-study building in Chapter 6.

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Photo 5 - *(top)* Andrea Cappello;

Photo 5 - *(bottom)* Enrico Cano;

Photo 6 - Picture of the Author;

Photo 7 - Frearson, A. (2013, 16th April). Tour Bois-le-Prêtre. *Dezeen (http://dezeen.com);*

Photo 8 - Unknown;

Photo 9 - Unknown;

Photo 10 - Unknown;

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CHAPTER 2
Building Integrated Photovoltaics: technologies and products
Building Integrated Photovoltaics: tecnologie e prodotti

ABSTRACT_ITA - *La necessità di ottimizzare le prestazioni energetiche del settore edilizio e di ridurne i consumi da fonti fossili ha portato a un sempre più vasto impiego di fonti di energia rinnovabile negli edifici. Una delle principali sfide, in quest'ambito, è quella legata alla ricerca delle migliori soluzioni per l'integrazione di sistemi per la produzione di energia pulita negli edifici, tenendo in considerazione non solo gli aspetti tecnici ed economici dell'installazione, ma anche quelli legati all'aspetto.*

Negli ultimi decenni, è emerso un nuovo segmento del mercato fotovoltaico, il Building Integrated Photovoltaics (BIPV), costituito da prodotti multifunzionali specificamente sviluppati per sostituire uno o più elementi tecnici e/o strati funzionali dell'involucro edilizio. I prodotti BIPV sono contemporaneamente componenti edilizi e fotovoltaici, in grado pertanto non solo di produrre energia pulita, ma anche di assolvere alle funzioni tradizionalmente svolte dall'elemento tecnico e/o strato funzionale sostituito.

Dopo aver passato in rassegna vantaggi e svantaggi derivanti dall'integrazione del fotovoltaico negli edifici, il capitolo porta avanti uno studio dello stato dell'arte del mercato BIPV, analizzando nel dettaglio sia le tecnologie fotovoltaiche esistenti dalla prima alla terza generazione, sia i prodotti presenti sul mercato, classificati secondo il ruolo tecnico-costruttivo assolto all'interno del sistema edilizio.

É stata inoltre condotta un'analisi delle principali potenzialità in termini di integrazione architettonica delle differenti tecnologie fotovoltaiche disponibili sul mercato nonché di quelle ancora in fase di sviluppo, facendo riferimento a una serie di parametri, qualitativi e quantitativi, considerati rilevanti in tal senso (dalle caratteristiche di produzione fotovoltaica alle proprietà tecnico-costruttive, all'aspetto estetico, ai costi…).

Alla fine del capitolo è tracciato un quadro dei principali indirizzi di ricerca e innovazione nell'ambito del BIPV allo scopo di definire un possibile scenario per lo sviluppo di nuovi prodotti e soluzioni.

ABSTRACT_ENG - *The growing diffusion of photovoltaics (and, more in general, renewable sources) for the energy supply of the building stock brought along several challenges. One of the most important has regarded the search for the best ways to integrate these systems for the production of clean energy into buildings, taking into account not only technical and economic aspects, but also those related to the appearance of buildings.*

In this context, a new segment of the photovoltaic market emerged, characterized by multifunctional components specifically developed for the technical-constructional integration of solar modules into buildings: the Building-Integrated Photovoltaics (BIPV). In particular, with the acronym BIPV is meant a multifunctional construction and PV element able to replace one or more building technical elements and/or functional layers. Therefore, the module is able not only to produce clean electricity, but also to provide other functions that are typical of the elements of the building envelope.

After having outlined the main advantages and issues related to the integration of photovoltaics into buildings, this chapter provides a study of the state of the art of the BIPV market, by focusing on both available solar technologies, from first-generation to third-generation PV, and products, classified according to their technical-constructional role in the building skin.

A review of main design possibilities related to the different photovoltaic technologies, either available on the market or emerging, has been carried out by referring to a series of qualitative and quantitative parameters considered relevant for the architectural integration of PV technology into buildings (i.e. regarding the electrical performance of the modules, their technological properties, appearance, cost and so on).

At the end of the chapter, an outline of latest research and innovation trends in the field of BIPV is drawn up with the aim to outline a possible scenario for the development of new products and solutions.

2.1. The Architectural Integration of Photovoltaics

In the last few decades, the necessity to optimize the energy performance of buildings and to reduce their carbon emissions has led to a more and more widespread use of renewable sources for the energy supply of the building stock. Active solar technology, in particular, has gained a solid position in the construction market; photovoltaics as well as solar thermal systems have become routine components of many building concepts (Schittich, 2003). One of the main challenges that came along with this regarded the search for the best ways to integrate systems for the production of clean energy into buildings, taking into account not only technical and economic aspects, but also those related to the appearance of buildings.

In this sense, PV plays an extremely relevant role: on the on hand, for its capability to produce clean energy to (completely or partially) satisfy electricity consumption of the buildings where it is installed; on the other hand, for the important aesthetic implications that it could determine on both building and urban scale. De facto, among the technologies for the production of renewable energy, PV is the one the more “naturally” encounters Architecture, allowing for interesting experimentations directly involving the building envelope (Scognamiglio, 2009).Nevertheless, in several cases, this latter aspect has been neglected or underestimated and, as a result, architecture and photovoltaics have been considered two worlds apart. Very often buildings presenting solar PV modules installed on their surfaces have been criticized for their lack of architectural quality (Schittich, 2003). The multitude of negative examples (Photo 1) against the initially quite limited number of positive ones reinforced this belief among the public opinion (Weller et al. 2010).

One of the main causes to this can be related to the higher cost or lower economic return expected, often erroneously, from a planning process that looks at photovoltaics as something more than only a system for the production of electricity, but that also focuses on its potential relapses on the architectural and constructional levels; another aspect that played a relevant role in this can be individuated in the lack of knowledge of possibilities and advantages deriving from a planning process where PV and architecture are two deeply intertwined fields.

Photo 1 - PV system installed on a roof in the historical centre of Arco, Italy

Photo 2 - Picture of a Solar Farm on agricultural land

Photo 3 - Aeral view of Lebrija 1 Solar Power Plant, Lebrija, Spain

Only in the past few decades, also thanks to the great technological advances occurred, a new way of conceiving photovoltaics gained a more and more widespread diffusion; according to it, photovoltaics are no longer considered as something to be added *ex-post* to a building and extraneous to it, but rather an integral part of the architectural project, from the concept, to building construction and management phases.

The **Architectural Integration of Photovoltaics** is one of the possible actions for the energy performance optimization of buildings and is characterized by the installation of PV systems for the energy harvesting of a building. Differently than a "simple" installation of PV modules onto one or more surfaces of a building or linked to it, in an integration the choice and the study of the features of PV system become an integral part of the design process, not only as regards the electricity production but also, more in general, as regards all those aspects related to the functionality and appearance of the building envelope. Becoming an integral part of the architectural project, photovoltaics — besides generating clean electricity — may also contribute to define and design building spaces and surfaces as well as provide performance of constructional kind, without of course compromising the performance of other building technical elements (GSE, 2007).

The integration of PV in buildings could represent a real alternative to large-scale solar plants (also known as "solar farms", Photos 2 and 3) that, according to many, are disfiguring our rural landscape, increasing the exploitation of the soil, and subtracting significant portions of agricultural land. Moreover, despite the optimal orientation of the modules and their high capacity, solar farms present several problems related to distribution losses, which are basically the result of a centralized energy model[1], and maintenance (e.g. difficult detection of malfunctions, shading on the panels due to dust, growth of vegetation, etc.). .

Perfectly in line with the above considerations, integrating photovoltaics, in particular, — and renewable sources, in general — allows clean energy to be produced right where it is consumed and most requested (cities and buildings), reducing to the minimum distribution losses and, especially, the exploitation of agricultural land. In addition, this perfectly encounters the new trends of the contemporary energy sector that is addressing growing attention towards distributed or decentralized energy models, as already highlighted in Chapter 1.

The integration of photovoltaics in the construction sector is a great opportunity that could enhance the penetration of active solar energy technologies in urban environments, offering millions of squared meters of sun-exposed surfaces available for the production of electricity. Just a figure to highlight the potential of this strategy: even attributing a relatively low efficiency (e.g. 5%) to the 23 billion squared meters of building roofs and façades fit for the installation of PV — calculated by referring to 14 among the most developed countries — a power of 1,000 GWp, equal to that of 1,000 nuclear plants, would be achieved (Pagliaro et al. 2008). At the same time, it represents also a significant challenge that goes beyond the production of electricity and involves the sustainable transformation and valorization of the territory, the creation of a new way of understanding the building project based on the concepts of «*Solar Design*» (Herzog, 1999).

2.2. Building Integrated Photovoltaics (BIPV)

In this context, a new segment of the Photovoltaic market emerged from the collaboration of the solar industry with the stakeholders from the construction sector and through the years has gained a solid position in the worldwide PV market, with very high expectations of growth. This segment is the Building-integrated Photovoltaics (BIPV), characterized by multifunctional components specifically developed for the technical-constructional integration of PV into buildings. More in detail, with the acronym BIPV is meant a multifunctional construction and PV element able to replace one or more building technical elements and/or functional layers. Hence, the module is able not only to produce clean electricity but also to provide other functions that are typical of the building envelope itself (such as thermal and acoustic insulation, weather protection, daylight modulation, and so on).

For the sake of a bigger completeness of this dissertation, following is reported the definition of BIPV modules provided by the European standard *prEN 50583-1:2014, Photovoltaics in Buildings — BIPV modules*:

«*…Photovoltaic modules are considered to be building-integrated, if the PV modules form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. […] The building's functions in the context of BIPV are one or more of the following:*

- *mechanical rigidity or structural integrity*
- *primary weather impact protection: rain, snow, wind, hail*
- *energy economy, such as shading, daylighting, thermal insulation*
- *fire protection*
- *noise protection*
- *separation between indoor and outdoor environments*
- *security, shelter or safety…*».

In this perspective, the BIPV modules turn out to be prerequisite for the integrity of the building's functionality. Indeed, in the case of removal of the integrated PV modules, the functionality of the building envelope is no longer guaranteed and the substitution of the PV modules with the adequate technical elements is required.

From the constructional point of view, photovoltaics can also be mounted on top of the already finished building skin — without providing any building function nor replacing any element of it — and be considered just as mono-functional technical devices added to the building, with their own supporting structure. In this case, we can refer to Building-Added or Building-Attached Photovoltaics (BAPV), which can be realized by recurring to "conventional" PV modules, i.e. whose only function is the production of electricity.

Growing attention – especially in the last decade – has been addressed towards novel PV technologies and multifunctional products aimed at the integration of PV in the architectural cladding. The BIPV market — bringing the PV and construction sectors together — is a steadily growing worldwide market, expected to see its total system capacity quintupled by 2017 with up to 4.6 GW of installations forecast through 2017 (Pike Research, 2012).

2.2.1. Potentials and Limits of BIPV

From the above-mentioned considerations, it is possible to underline one of the main characteristics of BIPV — representing, at the same time, its main advantage and, as it will be underlined later, its main complexity factor — and that is multifunctionality.

Being multifunctional building and solar components, BIPV products are able to replace conventional building technical elements and/or functional layers and to respond with one solution to a multiplicity of requirements, which “normally” are met by two ore more technical elements and/or functional layers.

This may lead to obvious saving in terms of building materials and, consequently, in the building cost; moreover, no additional support structures are required for the panels, which are an integral part of the building envelope, replacing it either partially or totally. Besides the material (and cost) savings, this also results into reduced construction times and costs: indeed, to integrate multifunctional BIPV products allows for simultaneous construction of the given building sub-system and of the PV installation.

In order to exemplify this, a possible solution for the installation of PV on pitched roof is illustrated in Photos 4 and 5. The only function provided by the solar panels on the left, simply added to the building roof structure that is finished with black tiles, is the electricity production. In particular, the solar panels require an independent supporting structure, that is in turn fixed to the roof. The solar tiles, on the right, are multifunctional: they are directly mounted as waterproofing (and finishing) layer of the roof, therefore they guarantee, as building components, the water tightness of the roof as well as the clean electricity production, without requiring any additional support structure. It is of relevance to note how necessary, in this case, is to link dimensionally and technically with appropriate elements the roof finishing with the PV-integrated tiles. The aesthetic effect of these two “operations” is not discussed in this phase, since it is not strictly linked with the technical-constructional role of PV in the building fabric[2].

Among the advantages of PV use in buildings, one must also consider the obvious reduction in building management costs related to the electricity self-production that, in case

Photo 4 - Building-added PV system, installed on a pitched roof with independent supporting structure

Photo 5 - Building-integrated PV system, installed as part of a pitched roof weatherproofing layer of surplus, can also be fed into the electricity grid, be sold to the energy provider and generate an income. This results even more relevant if we consider how, through the past years, national and international policies have established special premium incentives for building-integrated installations (it is, e.g. the case of France, Italy, Switzerland…); additionally, BIPV can also have access to other kinds of incentives (e.g. those related to green buildings and energy efficient renovations) that turn out to be important especially in those countries where incentives for solar PV ended — e.g. Italy — or are in course of exhaustion.

When BIPV solutions are appropriately incorporated into building design, they can provide several functions and benefits other than the electricity production. For example, well-studied systems can contribute to the improvement of the comfort inside the building. In this sense, it is worth to underline the potential relapses of the PV integration for the improvement of bioclimatic control capability of the building envelope (e.g. daylight control provided by PV modules used as shading devices, exploitation of the conversion heat for passive ventilation, etc.) and thus for the optimization of building energy performance. As it will be widely discussed in this work, this also translates into a reduction of energy consumption related to air-conditioning and heating systems, with corresponding economic savings in terms of building management costs.

Having said all that, after an initial outlay of planning and finance costs, the multifunctionality of BIPV products thus may have a favourable effect on the overall costs of a building project and on the amortisation of the PV system itself (Heinstein et al., 2013).

Besides the above widely discussed technical and economic benefits that can justify the adoption of building-integrated solar solutions, other reasons regarding less quantifiable aspects can be considered as adding-value features linked to BIPV. These are also reported synthetically in Table 2.1, where they are compared to those that are provided by BAPV.

In the perspective of building integration, solar modules enter the design process way earlier than in those situations when PV is considered just as a technical device to be added to the finished building; as a result, they become architecturally relevant components that, besides producing clean electricity and performing one or more additional functions according to the essential requirements expressed in CPR 305/2011, can also render an aesthetic value to the whole construction.

The aesthetic result of the PV installation represents one of the main critical factors for the spread and success of PV in the construction sector, especially when it involves the existing building stock and the heritage asset. De facto, the installation of solar modules might have a significant visual impact in the design of building façades or roofs, introducing in the language of architecture — especially, when referring to heritage contexts — new themes and complexities that, if not appropriately controlled in the design phase, might produce unsatisfactory results in terms of architectural quality and result poorly compatible with existing buildings. At the same time, the use of PV as a construction material and as an element of the architectural design, thanks to its “visibility” and its manifestly smart and green “nature”, nowadays represents for the public and the designers themselves a symbol of the technological progress as well as an icon of sustainability (Scognamiglio, 2010). This, besides contributing to increase the resale value of a building (Henemann, 2008), make BIPV a well-suited solution for those building owners who want to exhibit a sustainable image.

According to Weller et al. (2010), the multi-functionality deriving from the technical-constructional integration related to BIPV solutions could also enhance the acceptability of solar systems in buildings: «...*one way of improving the acceptance of building-mounted photovoltaics would seem to be allocating further functions to the solar electricity components, additional to just the generation of electricity. Only when PV technology becomes an intrinsic part of the building envelope, and is accepted as such, will it be able to unfold its full potential...*» (Weller et al. 2010, p. 38). Similarly, Munari Probst (2008) — dealing with solar thermal technology systems, although the same considerations can be translated into the PV sector as well — observed a higher acceptance of active solar devices installed onto

	BAPV				*BIPV*			
VALUE-ADDING FEATURES	*producing economic return*	*money saving in managing buildings*	*money saving in construction cost*	*building comfort improvement*	*producing economic return*	*money saving in managing buildings*	*money saving in construction cost*	*building comfort improvement*
Energy Production								
Electricity cost saving	■				■			
Electricity sale		■				■		
Incentives for PV	■				■			
Premium incentives for BIPV					■			
Contribution to the achievement of high rating in energy certifications	■				■			
Multifunctionality								
mechanical rigidity or structural integrity							■	
primary weather protection: rain, snow, wind, hail						■	■	■
energy economy, e.g. shading, daylighting, thermal insulation						■	■	■
fire protection							■	
noise protection							■	
separation between indoor and outdoor environments							■	
security, shelter or safety							■	
Architectural benefits								
Aesthetic Value	■				■			
Return of Image	■				■			

Table 2.1 - Comparison regarding the value-adding benefits of BIPV and BAPV

buildings when these are multifunctionally integrated as part of the building envelope. De facto, as the same author adds, the multifunctional integration of active solar systems into the building envelope makes it easier to deal with the formal aspects of the integration, providing a decisive advantage for the designer that have the possibility to compose with fewer elements (Munari Probst 2008) and with something they are able to manage with more "experience", i.e. building components.

The advances in the field of PV technologies allowed for a decrease in the cost of solar modules and, on the other hand, for the birth of new products with new features, particularly fit for architectural purposes: lightness, semi-transparency, flexibility, variety of color, grain and texture, integrability, etc. Nevertheless, at the same time, a great collaborative effort of all stakeholders involved (planners as well as R&D, building and PV industries) is still needed in order to help this technology overcome the hurdles that limit its deep penetration into the building sector throughout the world.

As it has already been highlighted, the higher initial cost compared to standard building-added PV solutions — that is a consequence the complex and multifunctional nature of BIPV modules — can be listed among the hurdles of BIPV technology, despite the already enumerated money-saving benefits expected in both the construction and management phases. It is also true that to implement BIPV solutions in practice may sometimes require an extra effort to building planners (Munari Probst & Roecker, 2012), which can result in extra costs, but they are significantly less relevant if PV is considered as an integral part of the design process and its potential is exploited to maximize building efficiency. Kaan (2009) adds also that architects are often not enthusiastic about the appearance of PV (and even BIPV) products, which are often developed by physicists only with efficiency in mind, and that they do not immediately think of using a solar panel as an interesting building material. The aforementioned obstacles to BIPV are in some ways linked to the lack of awareness among stakeholders and the underestimation of the advantages of this technology.

Finally, given the complex nature of BIPV products, belonging to PV and building industry and thus required to comply with electro-technical and building standards, the process of certification of BIPV products turns out a complicated and costly task for manufacturers. Binding standards have not been set yet and are in course of definition throughout Europe and that has been complicating the effective spread of new BIPV products and solutions.

Several steps forward have been made in the BIPV research for the development of new solutions with higher degree of integrability and lower costs of implementation as well as in the increase of acceptance and awareness among stakeholders, but the aforementioned aspects still represent a limit to the spread of BIPV technology in the building sector and lead many stakeholders to prefer «...*conventional, non-integrated and supposedly cheaper solutions...*» (Heinstein et al. 2013, p. 126) for mounting PV in buildings.

Despite the above-mentioned hurdles, the huge amount of realized examples of new-constructed and retrofitted buildings demonstrated BIPV as an multi-benefit, economically and environmentally sustainable solution for energy-efficient architecture.

2.3. Design Potential of PV: an evolution across different technologies

Also in the field of building integration, first-generation photovoltaic technologies, based on poly- and mono-crystalline silicon wafers, still dominate the market with a share that in 2013 accounted for 60% (Fraunhofer ISE, 2014). This is mainly due to highest nominal STC efficiency values among solar technologies, resulting in the smallest space requirement for the same power output, and to a more consolidated knowledge compared to the other commercially available solutions belonging to second and third PV generations.

Nevertheless, in the building integration sector, several other aspects may represent "restrictions" or, more simply, "requirements" to be accounted for in the choice of the optimal photovoltaic solution and thus may justify preferring one PV technology rather than another: among them, the (often non-optimal) orientation of the surfaces of the building where PV will find collocation, the materials used for the building skin, the necessity for more or less transparent solutions, more or less flexible solutions, and in general all additional performance aimed at the satisfaction of specific design requirements.

In this paragraph, a review of main design possibilities related to the different photovoltaic technologies available on the market is provided by referring to some parameters that are considered relevant for the integration of PV technology into buildings. The parameters, grouped according to the corresponding performance, are the following:

as for the ***energy production performance***:

- Performance at standard test conditions (STC):
  - Nominal efficiency;
  - Power Density;
  - Space requirement;
- Performance in real operating conditions;
  - Dependance upon the installation angle;
  - Sensitivity to diffuse and low-light conditions;
  - Temperature performance;

as for the ***architectural and constructional performance***:

- Surface properties:
  - Transparency/Translucency;
  - Color;
  - Homogeneity/Grain;
  - Reflectivity;
- Shape:
  - Bendability;
  - Rigidity/Flexibility;

as for the ***economic performance***:

- Cost:
  - Cost/Wp;
  - Cost/m^2.

2.3.1. First-generation PV technologies

The first-generation solar technologies are those based on the use of crystalline silicon, which is the most widely used material for the manufacturing of PV modules.

Mono-crystalline silicon (mc-Si) cells are obtained from high-purity silicon crystals and are characterized by the highest conversion efficiency value, but slightly higher pricesas well. The STC efficiency of the cells, in particular, ranges from 16-24% and best modules on the market have reached 20%.

Poly-crystalline silicon (pc-Si) cells derive from multi-crystalline silicon, obtained by means of an easier manufacturing process, which results into lower costs but also lower efficiency values compared to mc-Si. The STC efficiency of poly-crystalline modules indeed ranges from 14-18%, whereas single lab cells can also reach higher values.

Such technologies, especially the first one, display the highest efficiencies and, consequently, the highest power output per square meter (Wp/m^2) among all PV technologies. As already highlighted in the previous chapter, these two quantities are measured in standard test conditions and refer to optimal orientation, direct irradiance and 25°C temperature, conditions that hardly ever occur in actual installations.

In real operating conditions, the effective energy production (expressed in kWh/kWp) of crystalline silicon technologies shows instead several limits. First of all, first-generation PV systems are characterized by significant drop of performance deriving from the increase of temperature during real operations, when the temperature of the modules can even reach 70-80°C; the temperature coefficient — expressing the percentage loss of power per 1°C temperature increase — is about -0.45%/°C for both mc-Si and pc-Si and the highest among all solar technologies, leading to important drops in the PV performance compared to standard test conditions. Furthermore, crystalline silicon technologies are characterized by a significant dependance upon the angle of incidence of the solar rays (that is linked to the orientation of the modules) and upon the intensity of the direct and diffuse solar irradiation (which changes according to sky conditions — e.g. sunny or cloudy day — but can also drop significantly due to possible shading occurring on the PV modules).

When operating conditions get far from standard test conditions (e.g. vertical façade application not oriented towards south), other technologies, despite the lower efficiency, showed effectively higher energy production. Taking these aspects into consideration becomes even more important in the field of building integration, where the orientation of building surfaces is often subjected to a series of other decisions than the maximization of solar energy yield.

For the above-mentioned reasons, shading on the modules deriving from other buildings, dust, vegetation, etc. as well as self-shading deriving from chimneys, protruding volumes, etc. can negatively condition the real performance of crystalline silicon systems: «*...even one single partly shaded c-Si module will thus lead to a significant loss of power, not only in that particular module, but in all the others connected in series within the same circuit...*» (Heinstein et al. 2013, p.130).

However, crystalline silicon technologies remain the best in several applications (also in the field of building integration), such as, e.g., in those installations where optimal orientation and irradiation conditions are encountered (e.g. pitched roof, south-facing and free from shading) and where appropriate technical solutions for the rear ventilation of the panels are allowed.

The primary unit of both mono- and poly-crystalline silicon panels is the so-called “wafer”, which is the result of the manufacturing process that consists in the sawing of an ingot of mono- or multi-crystalline silicon into slices of approximately 0.2-mm thickness.

The shape of the mc-Si wafers can vary from round to square, to square with rounded angles, whereas pc-Si cells are typically squared. This difference is related to the different shapes of the ingots of monocrystalline and polycrystalline silicon from which wafers are obtained, with round and square cross-sections, respectively. Monocrystalline silicon ingot indeed is a cylindrical rod, obtained through the slow rotation of the silicon pulled-out from a melt and subsequently trimmed. Polycrystalline silicon rod has instead a square section, obtained by casting the liquid silicon into square molds where the material solidifies under strictly controlled temperature conditions into a series of crystals with diverse orientations (this is what gives the typical irregular grain of pc-Si cells). The dimensions of the wafers typically range from 100-150 mm.

The typical colors of the monocrystalline silicon wafers belong to the darkest tones of the cold region: blue, anthracite and black. Such appearance is due to the anti-reflecting coating, applied to the front side of the modules in order to maximize conversion efficiency. Without this coating, whose thickness is regulated in order to maximize device efficiency, mc-Si wafers would appear of a homogeneous grey (Photo 6a).

Typically, polycrystalline silicon cells are characterized by a frost-like and shiny blue to violet appearance, deriving from the many small crystals constituting the devices and, also in this case, from the appropriately dimensioned anti-reflecting coating. Before the application of the anti-reflective coating pc-Si wafers appear as silvery grey elements (Photo 6a).

In order to collect the electricity converted by the solar cells, highly conductive metal contacts are screen-printed on both sides of the wafers: this subtracts active area, reducing device efficiency, but could be exploited for particular aesthetic effects (Photo 6e).

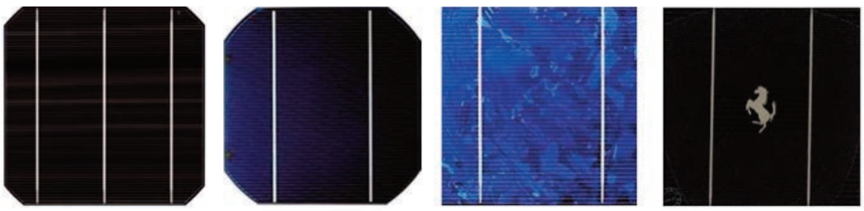


Photo 6 - *from left to right:*
a) grey mc-Si and pc-Si silicon wafers, before the antireflection coating application;
b, c, d) typical appearance of mc-Si wafers (black and blue square with rounded angles) and of pc-Si wafer (shiny blue, with irregular texture, square) after the antireflection coating application;
e) example of pc-Si wafer decorated by printing the metal used for contacts on the device’s surface (manufactured by ISSOL)

A certain variety of colors as well as of surface glossiness or opaqueness can be obtained in crystalline silicon technologies through the adjustment of the characteristics and of the thickness of the anti-reflecting coating, with corresponding modifications — most often a decrease — in the efficiency of the devices (Photo 7).

The thickness of the wafers can not stand below a certain limit, due to the fragility of the raw material; this results in a rigidity of the active layer of the solar panels, which in practice can only be planar elements. Limited curvatures are achievable through particular hot- or cold-forming processes (Photo 8).

Wafers represent the primary unit of first-generation solar modules and obviously have a significant role for the definition of their aesthetic appearance. The modular appearance that derives from connection of this small units into modules and panels is a peculiar feature of crystalline silicon panels. Such peculiarity can either be exploited to create particular motives and patterns or minimized if the maximum uniformity in solar panels appearance is pursued. In this latter case, besides reducing the dimensions of the edges, it is a common practice to replace the standard white plastic backing sheet of the solar panels with one, whose color is matched to that of the cells (Photo 9). However, darker backing materials increase the temperature of the modules due to higher solar absorption and this results into decreased efficiency of the panels.

Several module configurations are possible deriving from variations of the positioning, inter-distances, alignments, “density” and shapes of the wafer. A dedicated study on the possibilities deriving from “patterning” through PV wafers was provided by Baum & Liotta (2011). If the substrate of the module is a glass pane, the spaces between cells become transparent areas that allow light to pass-through the device. This, besides creating potentially interesting light effects, results into different degrees of transparency. Indeed, being the silicon wafers opaque, transparency can only be achieved by subtracting active area and this could be attained through distancing the cells (Photo 10) or riddling them with holes (Photo 11). These two “operations” for the attainment of some semitransparency allow reaching in principle any degrees of transparency but, of course, this corresponds to a growing decrease in active area and thus in the power of the modules.

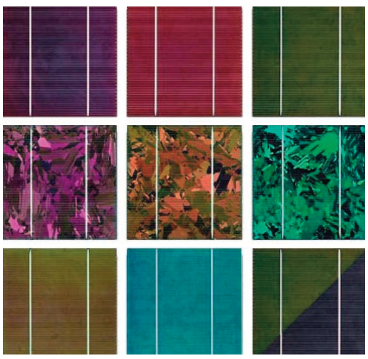


Photo 7 - Example of possible colors and appearances of pc-Si wafers

Photo 8 - Curved c-Si panels: electric catamaran *Alterstonne*, Kopf Solardesign

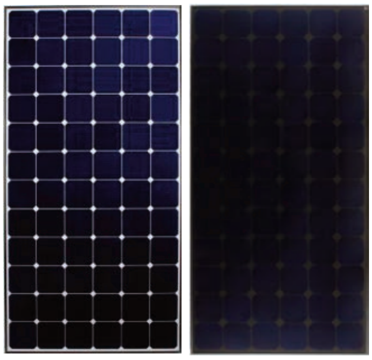


Photo 9 - SunPower modules with white and black substrate

Photo 10 - FKI Tower, Seoul, Adrian Smith + Gordon Gill Architecture, 2013

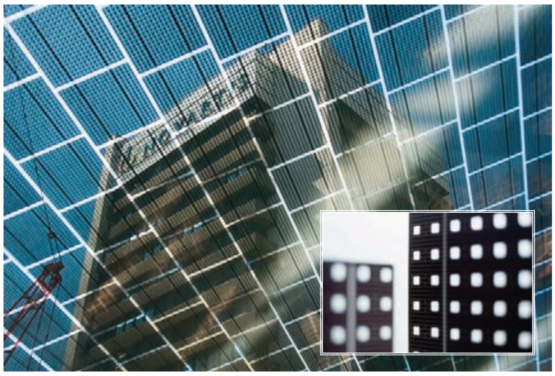


Photo 11 - Novartis Building, Frank O. Gehry, 2009 plus a detail of the solar cells used (Sunways)

The second method, consisting in the perforation of the PV active material, implies a sensible increase in the costs of production of the PV panels as well as the creation of a significant amount of manufacturing scraps.

In these cases, as highlighted by Baum R. (2011), rather than (semi)transparent modules, it is more correct to talk about "*light-through*" solutions, since the light is obstructed by the opaque wafers and passes through the interspaces among them, with the peculiar interplays of light and shadow. Obviously, the more transparent is the panel (i.e. the higher the non-active area), the less it is efficient. An appropriate balance should be pursued according to the requirements of each building.

The cost of first-generation PV technologies — and, especially, of poly-crystalline silicon panels — went down significantly during the last few years, due to: the increase (often helped by national and international instruments of financial support) of the market demand that allowed manufacturers making economies of scale; the growing competition coming from emerging countries in the PV market (China, above all); the often privileged Wp-based price evaluation of PV systems, inevitably favoring crystalline silicon technologies that are characterized by the highest efficiency values despite the expensive and "complex" manufacturing processes. It is clear how €/Wp prices are not suitable nor significant for multi-functional building-integrated applications, where a €/m^2 evaluation is more fit as well as compatible with the building industry; besides all performance-related parameters, this is also an important parameter to take into account when analyzing the potential of a solar technology for building-integrated PV applications. The basic price of crystalline silicon modules nowadays ranges from 120-200 €/m^2 (Heinstein et al. 2013).

2.3.2. Second-generation PV technologies

Second-generation solar technologies, commonly referred to as "thin-film" and aimed at the minimization of materials utilization, present a series of characteristics that result particularly suitable for building integration: lightness, flexibility, uniform appearance, large-area deposition processes, to name a few. In particular, second-generation technologies are

Figure 2.1 - Flexible CIGS solar module (ASUN-TFLEX, www.a-sunenergy.com)

Figure 2.2 - Flexible a-Si solar module (Sunerg UNI-SOLAR®, www.sunergsolar.com)

characterized by the use of different semiconductors, which are deposited on various kinds of substrates (e.g. glass, plastic, metal, etc.) in the form of a very thin films of micrometrical thickness (1-2 microns). Such semiconductors can be:

- Silicon, in amorphous (a-Si) and micromorph (μm-Si) form;
- Copper Indium Gallium diSelenide (CIGS) or, without gallium, Copper Indium Selenide (CIS);
- Cadmium telluride (CdTe).

Other minor technologies emerged the market, but this study will focus on the three above-mentioned.

As already hinted above, due to the micrometrical thickness of the active layer, thin-film technologies result significantly more lightweight than first-generation technologies. Moreover, thanks to their thinness, semiconductor films are flexible and, when applied onto metal sheets and/or plastic foil substrate, can therefore allow for the attainment of flexible solutions (such as, for example, those shown in Figures 2.1 and 2.2). However, they can also be applied to rigid substrates. This represents an interesting advantage also for their integration in buildings and allows for the application of photovoltaics in new ways, basically impossible to be explored with first-generations technologies. De facto, some of the most successful products in the field of BIPV are the flexible laminates, which are specially suited for large industrial flat roofs.

Besides the above-cited aspects, also the uniformity of the appearance results particularly interesting for the architectural integration and thin-film solutions can be considered more suitable than "patterned" crystalline silicon solutions, if a homogeneous appearance is searched for.

The aforementioned advantages, along with the good performance in non-standard operating conditions, may compensate, in several applications, thin-film module conversion efficiencies, which are lower than those of first-generation technologies and, at the same time, may explain the success expected for thin-film technologies in the near future within the building-integrated PV market with a forecasted growth at a CAGR of 19% between 2013 and 2019 (TMR, 2014).

2.3.2.1. Silicon-based thin-film modules: amorphous and micromorph silicon PV

For silicon-based thin-film modules, the STC efficiency ranges from 4%-6% for amorphous silicon (a-Si) technology and can reach up to 10% (with perspective for further increases) for micromorph silicon (μm-Si) technology. This means that a wider area of thin-film silicon-based solar panels is required to obtain the same installed power as first-generation technologies.

As already underlined, nominal efficiency is not sufficient to describe the effective production in real operating situations, which hardly ever coincide with ideal lab conditions, according to which the performance of PV solutions are most commonly defined and compared. For example, compared to first-generation technologies, silicon thin-film modules are less affected by the high temperatures that are reached during operations: the temperature coefficient of amorphous silicon is -0.21%/°C, i.e., in absolute value, it is less than half than that of crystalline silicon; the temperature coefficient of micromorph silicon is slightly higher, -0.25%/°C, but still implies a better performance than crystalline-silicon modules when operating temperatures increase. Another important aspect regards the less significant loss of performance under conditions of lower irradiation (e.g. cloudy sky, partial shading...). Because of the aforementioned aspects, in certain conditions, the annual energy production of silicon-based thin-film systems can provide a higher output then crystalline silicon solutions. Such conditions can occur quite frequently in the field of building integration, because of the presence of other buildings, of vegetation, of chimneys and other possibly shading structures or even because of the impossibility to provide an adequate rear ventilation to integrated PV modules. Therefore, a correct study of the possible installations of PV can not focus exclusively on panels efficiency (i.e. on the space requirement and power density in W/m^2) as provided by PV manufacturers; rather, it can not do less of taking into account also the above aspects, which can justify preferring, in several cases, thin-film solutions.

Also in thin-film silicon panels, the active layer is opaque to light, hence transparency is achievable only by subtracting active area and letting the light through glass-based panels. However, differently then first-generation technologies, it is possible to obtain semi-transparent modules with a more uniform appearance. This can be achieved through laser-scribing processes that can micro-perforate the active film according to different pattern shapes

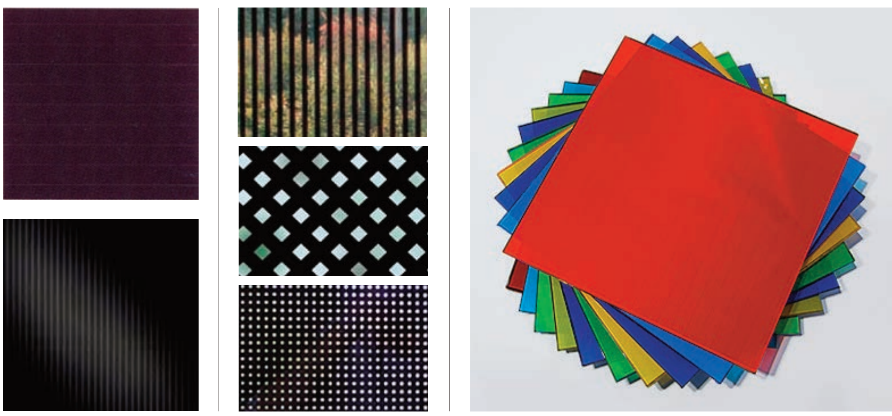


Photo 12 - *(left)* Example of typical red-brown a-Si and black μm-Si module;

(middle) different patterns for different transparency levels, defined in the PVAccept project;

(right) a-Si modules in different colors, provided by Onyx Solar

and densities, obtaining different transparency effects (Photo 12). This additional manufacturing step for the achievement of diversified transparency degrees has the downside to produce significant materials scraps but, most importantly, reduces significantly the active area and consequently the solar yield of the devices. Baum (2011) defined these semi-transparent solutions as "see-through" modules, due to this specific characteristic in terms of light transmission.

Speaking about colors, a-Si film is typically characterized by a brownish uniform appearance, whereas μm-Si film is black. However, a great variety of colors is possible in see-through modules, by varying the color of the substrates, whether they are transparent or opaque, with results that do not compromise the uniformity in the appearance of the products. In Photo 12, also some samples of the commercial solutions of colored and translucent PV glass, provided by the Spanish BIPV company Onyx Solar, are shown: products are available, according to customers' requests, in different degrees of transparency (from 10-40%) and in a great variety of colors (ranging from blue to green, red to yellow). It is important to note that it is not the active layer to be colored, but the substrate[3].

The uniformity in panels appearance becomes the added value that can distinguish the quality of different solutions (Photo 13, 14). It should not however be forgotten that this interesting color effect comes at the expenses of the efficiency of the products. Indeed, a clear substrate heats up in a minor measure than a clear one, which absorbs a lower amount of solar energy; moreover, the most uniform of the appearances are related to a bigger amount of material subtracted from the active film.

Finally, speaking about the cost per square meter, silicon-based thin-film modules are remarkably less expensive then first-generation modules, thanks to smaller quantities of semiconductor required (cells are from 100 to 200-times thinner than wafers) and to manufacturing based on high-capacity and large-area deposition processes (far different than the slicing of the ingots into small cells). The basic price of silicon thin-film modules nowadays stands at about 40 €/m^2 (Heinstein et al., 2013) but it must be noted that higher surfaces of solar modules are required for the same peak power than first-generation technologies, which in terms of cost per watt-peak, still remain the most competitive.

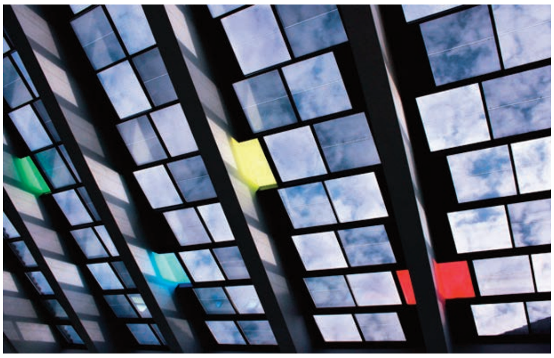


Photo 13 - Bejar Market, Salamanca, 2012: see-through a-Si modules by Onyx Solar, integrated as skylight

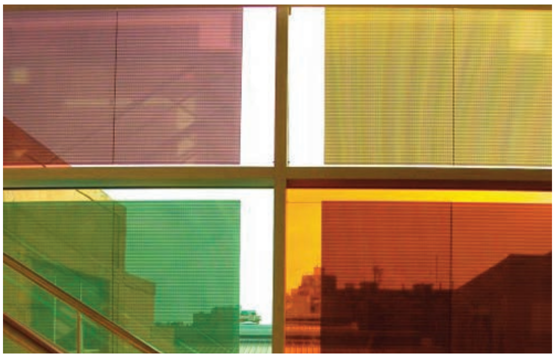


Photo 14 - Schott Iberica Building, Barcelona, 2008: Schott Solar aSi-thru modules installed as window infills

2.3.2.2. CIGS and CIS thin-film modules

Thin-film modules based on Copper Indium Gallium diSelenide (CIGS, or, if without gallium, Copper Indium Selenide, CIS) are promising solar technology in the BIPV field.

The laboratory efficiencies have overcome 20% (Jackson et al., 2011). In May 2015, a 3-and-half-year Horizon 2020 project, called "Sharc25" and aimed at the achievement of the goal of a 25% efficiency for CIGS modules, has started, demonstrating the potentialities of this technology[4]. Average CI(G)S modules efficiencies, however, still remain notably lower, around 11-13%. Top commercial modules on rigid substrate have reached values above 15% (Jelle et al., 2012). The top efficiency reached in flexible modules is instead equal to 12.6%[5]. Modules based on this technology show better energy production (kWh/kWp) than crystalline silicon, due to good and durable operating performance and to better — despite still quite high, compared with other thin-film technologies — temperature coefficient related to maximum power (-0.35%/°C).

The typical color of CI(G)S modules goes from homogeneous dark grey to black and through the appropriate coatings, it is possible to obtain shiny and/or mat surface characteristics, allowing for elegant applications (Photo 15, 16). Semitransparent solutions are basically not present in the market, unless of some attempts made by some companies (e.g. Manz).

The lately decreased, but still quite high costs of CI(G)S technology (indicatively 100 €/m^2) represents a limit for its spread in the BI(PV) market, but expectations of a decrease of costs (due to increase of production, optimization of the highly efficient roll-to-roll manufacturing processes) are promising for the next future[6]. However, the main problem of this technology is that it is based on scarce elements, which make it unlikely that they will be able to achieve terawatt-scale deployment at reasonable cost (MITei, 2015). Among the companies active in the production of modules based on CIGS technology we can list: Soltecture GmbH (former Sulfurcell Solartechnik, specialized in BIPV systems), Global Solar Energy Inc., Manz AG.

Photo 15 - Sulfurcell CIGS modules integrated on the façade of Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin, 2011

Photo 16 - Manz CIGS modules integrated as façade cladding elements in the House of the German Team (by Technical University of Darmstadt) at 2009 Solar Decathlon

2.3.2.3. CdTe thin-film modules

Cadmium Telluride (CdTe) photovoltaics are provided of the lowest production costs among thin-film technologies (Jelle et al. 2012) and are considered among the most promising for wide-scale applicability (Khrypunov et al., 2011). CdTe technology is indeed characterized by costs ranging below $0.5 per watt (already at the end of 2013[7]) and by good efficiency levels: worldwide leader First Solar achieved an efficiency of above 20% on the cells and above 17% for the modules. Temperature coefficient ranges from -0.20 to -0.30 %/°C, which are far below than those of first-generation technologies.

For all the above reasons, CdTe dominates thin-film market and in 2013 represented half of the share of this segment of PV industry, with a wide application in large-scale installations where it represents, in many's opinion, the only technology with the potential to overcome crystalline silicon in terms of cost-effectiveness. Nevertheless, the toxicity of cadmium — which is an important environmental concern related to this technology, mitigated by the recycling of CdTe modules at the end of their life time — and the rare abundance of tellurium in the earth's crust seem significant obstacles to its growth.

The color of the modules can either be dark green or black. With the CdTe it has been possible to obtain modules with very uniform appearance. Flexible solutions are possible, whereas semitransparent solutions are not present in the market.

Despite the great potentialities, indeed, the CdTe market leader, First Solar has not yet expressed interest in BIPV (NanoMarkets, 2014). Although in several cases, third parties have used this company's modules for the manufacturing of multifunctional products for building integration, the share of CdTe technology within the BIPV market still remains negligible to date[8]. Indeed, it is very rare to find BIPV installations worth to mention (even if, in this sense, it could be interesting to cite the first attempts of the German company, Calyxo GmbH), but rather building-added ones can be more easily encountered.

Photo 17 - Example of a Cadmium Telluride photovoltaic array

Photo 18 - Example of Cadmium Telluride photovoltaic modules integrated as roof elements

2.3.3. Third-generation "Organic-based" PV technologies

The above-discussed photovoltaic generations represent approximately 100% of both PV and BIPV markets. Nevertheless, the Scientific Community in the field of the PV sector acknowledges high potentialities in the field of building integration also to third-generation solar technologies, which have recently passed the pre-industrial phase and are currently entering the BIPV market with the first important applications. These are:

- Organic Photovoltaics (OPV);
- Dye-Sensitized Solar Cell (DSSC or DSC).

Commonly referred to with the adjective "organic-based" — due to the presence of raw materials involving organic compounds, indeed — these solar technologies have been gaining more and more attention also because they are able to provide real answers to the new trends solar energy sector is heading towards, especially as regards the BIPV segment: lightness, flexibility, versatility, sustainability of materials, cost-effectiveness.

As regards the cost-effectiveness, in particular, it is mainly linked with the possibility to make use, for their manufacturing, of processes that are typical of printing industry (such as serigraphy, ink-jet and, on flexible substrates, also roll-to-roll printing) and allow simplifying the production as well as reducing its costs (both economic and environmental).

The flexibility related to this type of production opened numerous scenarios for the use of such "organic-based" technologies not only in the building integration sector, but also in a variety of novel applications (e.g. application on textiles, automotive, and portable off-grid devices), where such technologies can really manifest their potential against all other solar technologies.

A great customizability in terms of color, design and transparency are very important aspects especially in the field of the BIPV market, because they represent a disruptive novelty compared to first- and second-generation technologies, which are essentially based on the use of opaque and dark-colored materials. There, a quite limited aesthetic versatility, compared to third-generation devices, can be achieved due to an industrial production process harshly customizable (Riccitelli at al., 2014) and generally it occurs at the expenses of the efficiency of the devices, also determining a certain increase in the cost of the products. The opportunity to have devices where the active solar layer can be easily manufactured in various degrees of transparency, in different colors and "shapes", represents a great advantage in the perspective of building integration.

Still, durability, stability and efficiency represent key-issues to be addressed in order to help third-generation technologies to become a more relevant and consolidated presence in the photovoltaic industry.

Organic-based PV offers nearly unlimited possibilities to design of photovoltaic products. The challenge of the future will be to provide suitable products finding a balance between aesthetic and economic requirements. Several investments are also required to help realize the actual low-cost potential of these technologies.

2.3.3.1. Organic Photovoltaics (OPV)

The structure of OPV is characterized by a sandwich structure where the active semiconductor (that can be synthesized from many different molecular and polymeric materials) is interposed between a transparent substrate, which is coated with a thin film of transparent conductive oxide, and a metallization that functions as counter-electrode. The transparent substrate can either be rigid (glass) or flexible (typically, Poly Ethylene Terephthalate or PET).

Record efficiencies for lab-scale solar cells (approximately 1 cm^2) are above 12% for completely opaque devices[9], whereas a 7.2% record efficiency has been reached in 40% transparent solar cells[10]. Both records belong to the German company Heliatek[11], which has recently developed its pilot plant for the manufacture[12] and commercialization of OPV films, HeliaFilm®, in different colors and with different levels of transparency.

Despite the lower efficiency values, OPV technology displays a better angular and diffuse light sensitivity and temperature behavior than first- and second-generation PV.

In particular, OPV modules keep or even increase their performance at operating temperatures (i.e. positive temperature coefficient), differently than cells based on inorganic semiconductors, losing a relevant part of their efficiency, when temperature — as always occurs in operating conditions — gets far from 25 °C, corresponding to STC. As a consequence, the rear ventilation of the modules is not required anymore and therefore OPVs could be easily applied as the outer layer onto any construction materials.

The main advantages of the OPV technology lie:

- in the lightness of the devices, linked to the small thickness of the active materials, resulting into lower costs and minimizing structural requirements;
- in the completely organic nature of the devices as well as low-embedded-energy and potentially very low-cost manufacturing processes, increasing the both economic and environmental sustainability of this technology;
- in its great versatility that makes this technology particularly suitable for BIPV applications.

First of all, solar modules can come in a range of colors — ranging from grey, green and blue, but also in the red area — either on opaque or transparent substrates. The transparency of the devices, in this case, is not achieved by subtracting active area to the devices, whereas it is the photovoltaic layer itself that is translucent: therefore, we are not in front of either *see-through* nor *light-through* solutions, as defined in the previous paragraphs (Baum, 2011).

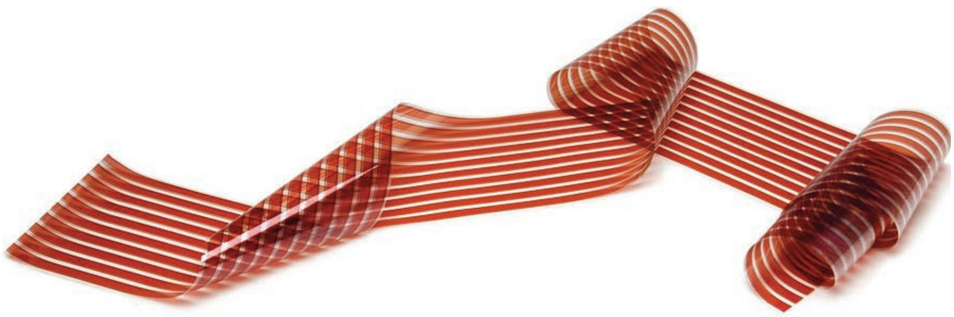


Photo 19 - Organic Photovoltaic (OPV) film

Sensibly higher degrees of transparency can be achieved, naturally corresponding to a lower yield than in opaque solutions, but not as relevant as that related to the subtraction of active area. For example, the German leader in OPV technology, Heliatek, has a target of 50% transparency for 2015 with an efficiency around 7% (Figure 2.3); this does not correspond to a halved efficiency with respect to the opaque device as it would be in the first PV generations.

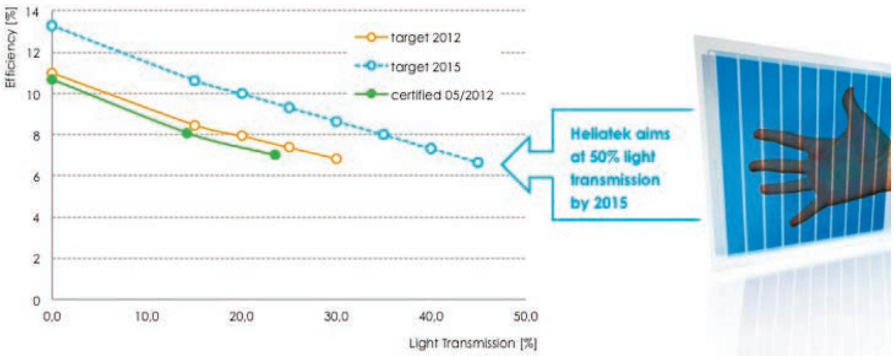


Figure 2.3 - Relation between efficiency and transparency of Heliafilm technology, with indication of the target established for 2015: 7% efficiency and around 50% transparency (Heliatek.com)

Moreover, due to the cost-effective printing procedures, a great customizability in the design is possible, allowing for the attainment of different shapes and looks: it is worth to mention the activity of the German company, Belectric OPV[13], which has developed the devices that are installed on the German Pavillion at the 2015 Milan Expo and has in the design customizability one of the main strong points of their OPV-based solar devices (Photo 20). Kalowekamo & Becker (2009) underlined the low-cost potential of OPV technology and estimated manufacturing costs to range from 48.8 $/m^2$ (low estimation) and 138.9 $/m^2$ (high estimation), resulting in a module cost between $1.0 and $2.83/Wp (considering a 5% module efficiency). The main challenges for this technology to become a more relevant presence in the PV market and meet the estimations of a $87 million market by 2023, regard the efficiency increase up to 15% and the achievement of a lifetime of 15-20 years (Zervos et al., 2013). As stated by Erk (2012), the operating lifetime still needs to be improved significantly through the development of high-performing, durable and affordable encapsulants (used for the enclosure and protection of devices) able to respond to different climate conditions, installations and exposures.

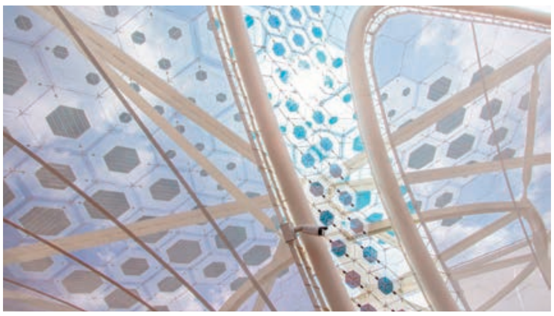


Photo 20 - German Pavilion, Milan Expo, Schmidhuber: OPVs integrated in the membrane-covered shelters

Photo 21 - Heliatek's HQ, Dresden: Heliafim laminated into glass by AGC Glass Europe, installed as sunshades

However, the aesthetic versatility is an added value that already enabled this technology to approach the BIPV market with first pilot installations that represent a novelty in the PV panorama, being used in ways that "conventional" PV cannot be used. In this sense, it is important to underline the great advances in the field of OPV technology — with particular regard to the BIPV segment — due to Heliatek company. Its technology, HeliaFilm®, is a ultralight (0.5 kg per square meter) and less than 1-mm thin OPV film, available in different colors and with various levels of transparency as well as characterized by a homogeneous appearance. All these features makes this product perfectly suitable for integration on several kinds of substrates: glass (Photo 21), metals, plastic foils (Photo 22), concrete (Photo 23). This latter represents, in particular, a great novelty in the BIPV industry, possible thanks to the peculiar characteristics of the OPV technology (e.g. the optimal thermal behavior, reducing the needs for rear cooling or ventilation of the modules).

Recently, in may 2015, Europe's first solar concrete wall has been inaugurated at the headquarters of RECKLI GmbH in Herne, Germany. RECKLI (which is the worldwide leader in the design and manufacture of elastomeric polyurethane formliners and moulds for patterned concrete) directly collaborated with Heliatek for the design and development of these concrete façade elements integrated with green opaque HeliaFilm®. The total installed power on the south-west oriented wall is 1 kWp and is expected to supply around 500 kWh of electricity per year[14]. This pilot project is characterized by a three-row façade of concrete panels, onto which are installed Heliatek OPV films, for a total area 16.80x3.50 m.

Another concrete-based pilot installation of HeliaFilm® was delivered in RECKLI Chinese headquarters in December 2014, on 20-square-meter surface (exposed to south, east and west) for a global power of 0.62 kWp (620 Wp)[15]. The market entry for this solution is planned for 2017.

Besides the above-mentioned companies, other companies such as Mitsubishi, Solarmer and eight19, are working on the development of organic solar cells and are preparing to enter the market by initially targeting smaller niche markets. On the other hand, Konarka Technologies which had started the commercialization of flexible OPV products already in 2010, filed for bankruptcy in 2012 and failed to survive the competition, due to high costs coupled with limited lifetimes.

Photo 22 - PVC-based membrane air dome in Berlin, implemented by Heliatek with PARANET

Photo 23 - RECKLI's HQ, Herne: detail of the Heliafilm applied to concrete cladding panels

2.3.3.2. Dye-Sensitized Solar Cells (DSC)

In its relatively young history, third-generation Dye-Sensitized Solar Cell (DSC, or DSSC) technology has been widely investigated and has finally started to enter the BIPV market in the last couple of years[16]. Among third-generation technologies, it can be considered the closest to the industrialization phase (Artuso et al., 2013).

Dye-sensitized Solar Cells, invented in the early '90s by Michael Grätzel and Brian O'Reagan at the Ecole Polytechnique Fédérale de Lausanne, EPFL (O'Reagan & Grätzel, 1991), are composed of a multi-layer sandwich structure, by two substrates, where the active layer is a micrometrical-thick sequence of highly biocompatible materials (the a-toxic and biocompatible TiO_2; the photoactive dye, based on organic and/or metallic-organic molecules, coming from artificial synthesis and/or available in nature).

Still, despite the great improvements towards better performing and enduring modules, it represents a niche in the solar industry due to limited stability, low levels of efficiency and high manufacturing cost (despite the real but yet unexploited low-cost potential). In particular, as regards the efficiency values, lab devices have already overcome 15% efficiency, making this technology competitive with second-generation technologies, while modules range from 4% up to a maximum of 8%. The lowest efficiencies, in general, correspond to more transparent devices, whereas the highest to the opaque ones.

Despite the low levels of efficiency, such electro-chemical solar devices, indeed, maintain high efficiencies under all kinds of light conditions. This is mainly due to the fact that, differently than other PV technologies of first and second generation, DSCs show their peak of conversion efficiency (or, however, maintain their level of efficiency) in conditions of lower light intensity than direct irradiation of STC (1000 W/m^2), e.g. diffuse light. As a consequence, DSC panels remain efficient also in absence of an oriented installation facing south, as they produce high proportional levels of power from "global" radiation –- reflected and diffuse light — with notable advantages especially in terms of façade integration. Thus, the method of evaluation of a solar module peak power, measured in Wp and referred to the direct 1-sun irradiation, can lead to an underestimation of the effective energy performance of this third-generation technology. DSCs even maintain good efficiency under artificial light, so that companies such as Sony, Sharp and Fujikura[17], active in the field of the industrialization and commercialization of this technology, indeed, see in its indoor use an important direction of development. Moreover, DSC application on glass substrates permits the construction of bifacial devices that, for example, when installed as elements of a building envelope, are able to catch the light coming from both the external and indoor environments, thus increasing the time of exposure of the cells that might also take advantage — quite efficiently, as underlined — of the artificial light. Indeed, DSC technology is also an efficient and appealing technology for energy harvesting even from artificial light in buildings (De Rossi et al., 2013). The bifacial configuration of the devices could also be exploited outdoor, for example, for the installation of vertical dividers (parapets and divider walls of roof-top terraces and/or bridges, etc. as well as noise barriers) or either of vertical roof-top installations. If aligned north to south, bifacial DSC modules would be able to catch, in the morning hours, the energy coming from the rising sun on their east side and, in the afternoon, the energy delivered by the setting sun on their west side (Muller, 2014).

As regards the temperature coefficient (related to the maximum power) of the DSCs is the best among PV technologies and equal to -0.005 %/°C, against e.g. -0.45 %/°C of c-Si and -0.2 %/°C of a-Si (Heinstein et al., 2013); in some cases, it has also been measured as a positive value. This means that real operating temperatures — which almost in every case are notably higher than the 25 °C of the STC efficiency calculation — do not generate any relevant drops in DSC performance and can even provoke an improvement in device efficiency.

Different outdoor tests have demonstrated that, thanks to these characteristics, DSCs, despite the low conversion efficiency, are able to produce yearly 10-15% more kWh of energy compared to crystalline silicon technology, in real operative conditions and being the power installed the same (Toyoda et al., 2004). This gap sensitively increases if the orientation of the panels is not the optimal one – inclined in order to face south — and can even reach 60%, in north-oriented vertical installations (Tanabe et al., 2010). The lower efficiency, as already highlighted, implies larger space required in order to achieve the same output power as crystalline silicon technologies, but the effective power yield shows that DSCs have the potential to be competitive compared to both first- and second-generation technologies.

Besides the above-discussed energy performance, DSCs have been addressed a great attention by the Scientific Community as one of the most promising among the emerging technologies for building integration, due to their peculiar versatility in terms of color, transparency, design, etc. De facto, DSCs can be easily printed on different kinds of support, either rigid or flexible, transparent or opaque, from glass to plastic, from metal to ceramics, through relatively low-cost and potentially highly-productive manufacturing processes.

The typical configuration of DSC modules is characterized by a series of interconnected rectangular narrow cells[18] with highly transparent non-PV spaces between them, where an encapsulating material (typically a resin or glass frits) is used in order to enclose and separate the cells among each other (Photo 24). The drop in the DSSC efficiency from lab to module scale is also due to this “non-active” portion of the final device, besides the other defects coming with the scaling-up. Different types of module configurations have been developed, resulting into different possible effects in terms of “design” and transparency (Photo 25).

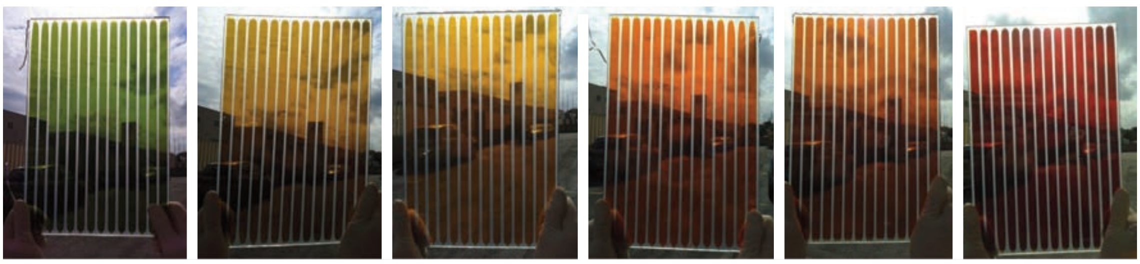


Photo 24 - Modules in different colours (green, bronze, yellow, orange, red, purple) developed by DyePower Consortium, Italy

Several studies regarding manufacturing processes and device compositions are currently ongoing and aimed to maximize the “active” portion of dye-sensitized solar modules without compromising their efficiency or either to achieve wholly active devices through the insertion of “charge-collectors”.

The transparency of dye-sensitized solar cells may be tuned, through an adequate “design” of the dimension of the particles as well as of the thickness and structure of the layer of TiO_2 semiconductor and dye. Even though a higher value of transparency may imply some reduction in the efficiency of the cell, the possibility to easily regulate it according to the geo-climatic conditions of the context of installation, design choices, global consumption foreseen for the building and the indoor comfort requirements represent an aspect of extreme interest in the field of “integrated” design. Also in this case, as in the OPV case, the active layer is translucent and can be more or less transparent; values above 40% transparency have been achieved with corresponding but not proportional decrease in the efficiency of the devices.

In the same way, by choosing carefully the different dye formulations and calibrating thicknesses as well as the characteristics of the nano-materials composing the devices, it is possible to achieve a great variety of results in terms of device colorations (from green to grey, brown, red, purple, orange, yellow, blue etc.). DSC modules on transparent glazed substrates basically look like a colored glass, creating interesting light-effects for those who are behind them. Despite the typically “striped” configuration, from afar such modules display a homogeneous appearance due to the uniformity of the active part of the devices.

In addition, different tones of the same color can be achieved in the same device through adjusting the thickness of layers, allowing to achieve different “active” drawings in the solar modules and multiplying the “design” potential related to this solar technology (Photo 26). Due to the printing-based processes behind DSC technology manufacturing, all these possible “modifications” in the appearance of the dye-sensitized solar modules can be quite easily obtained, without significant additional costs. DSCs indeed allow a large range of products to be manufactured from the same line. Desilvestro et al. (2009) state: «...*the optical transparency*

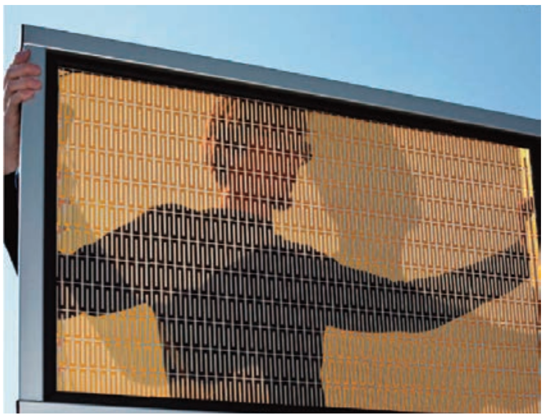


Photo 25 - Prototype of a 60x100 cm DSC amber-coloured module, manufactured at Fraunhofer ISE, with the so-called “meander-type” connection

Photo 26 - Multi-colored prototypes of DSCs manufactured by Sony (obtained according to patent n. US2011155223, by M. Morooka et al., 2009) *and coloration of DSCs can be easily varied in virtually unlimited combinations through the adjustment of the thickness and type of TiO_2 film as well as the nature of the dye, without requiring any additional manufacturing hardware*» (p. 238). This gives DSC technology a wide mass-customizability that is for obvious reasons a key success factor in the BIPV market.

As regards the cost, materials still have the major contribution to the total cost of DSC modules, despite the very low quantities used in the micrometrical layers of the devices. Several studies have been conducted and demonstrated the potentialities linked to the low-embedded-energy and relatively low-cost manufacturing process of DSC technology. One of the most detailed was elaborated in the field of the European Project "Robust DSC" estimated a possible market cost range from 0.63 to 0.86 €/Wp and an initial sale price of 1.3 €/Wp, corresponding to 90 €/m^2 for 7%-efficient DSC modules (Kroon et al. 2013). Nowadays, several investments have been made and several companies have started to enter the market, but those costs are still far from being reached.

A large number of companies and research centers activated collaboration networks and promoted the birth of consortium and joint projects with industries active in the field of the production of building materials — especially glass, plastic and steel — for the industrialization and commercialization of large scale DSC products for the building integration. According to a study made in 2012 on a sample of 30 companies active in the DSC field, about the 80% of those is developing solutions that foresee the integration of the DSCs on glass substrates (Morini, 2012). Among them, it is important to cite: Dyers (Italy), Dyesol (Australia), Exeger (Sweden), g2e (Switzerland), Solaronix (Switzerland) and Pilkington America (USA); all these companies are involved in pilot production projects aimed at the commercialization of DSC-based glass for BIPV. For example, it is worth to mention the joint venture of the Australian company Dyesol[19] with South-Korean Timo Technology (www.timo.co.kr), producing and supplying DSC modules using Dyesol materials, technology and know-how. Such collaboration allowed for a "showcase" installation in 2012 of DSC-powered solar windows at Seoul City's Human Resources Development Centre office complex (Photo 27).

Photo 27 - DSC Solar Windows at Seoul City's Human Resources Development Centre office complex, Seoul, 2012: view from the inside

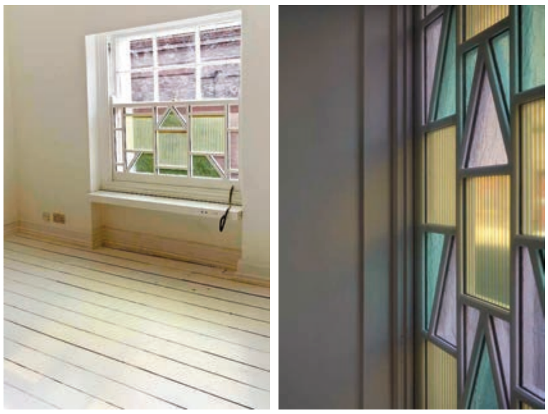


Photo 28 - "Current Window", Marjan Van Aubel, 2015: DSC-integrated windows recharging small electrical devices

The solar windows were manufactured by a large Korean glass fabrication company specialized in window and door systems, Eagon Industrial Co. Ltd., which integrated Dyesol-Timo solar modules into the glazed infill elements, characterized by a geometric, multi-colored pattern.

Speaking of dye-sensitized solar cell windows, it is worth to mention the work of the Dutch designer Marjan Van Aubel, who designed of a series of energy-harvesting windows, named "Current windows"[20]. By updating and re-proposing the traditional design aesthetic of stained glass, through the combination of DSC modules and colored translucent glass pieces, the designer has developed energy-harvesting windows with pleasant aesthetics and with a high integrability potential in the field of the energy retrofit of existing buildings. The (quite limited) energy harnessed by the solar modules, manufactured by Solaronix, is collected into batteries hidden inside the window ledge, where USB ports for the recharging of small portable devices are integrated as well.

Coming back to Dyesol, the Australian company also partnered with Europe's second largest steel manufacturer, Tata Steel Europe, for the development and manufacture of DSC modules on steel substrate, for building integration. Such modules are 3-meter long and 1-meter wide and are ready for mass commercialization. In 2013, Dyesol also partnered with Pilkington North-America for the development of glass-based DSC modules.

In this dissertation, it is also important to mention the activity of the Swiss company g2e (glass2energy), born in 2011. This Swiss licensee of Grätzel technology has recently entered the market with large-scale (600x1000 mm; 1000x1000 mm) DSC panels, called "Energy Glass", that have among the lowest prices in the field of DSC technologies thanks to the starting up, in January 2015, of an industrial production line that will reportedly be able to produce, at full operation, approximately 10,000 modules per year. The "Energy Glass" products are available in different levels of transparency, colors (e.g. red, green, orange), design (with vertical and/or horizontal, wavy and/or straight DSC strips as well as different possible logos printed on them) and are characterized by very high active area (around 80%). As regards the energy performance, some information are provided in Table 2.2[21].

PERFORMANCE PARAMETERS	2014	2016
Power Density (W/m^2)	40	55
Yearly production per square meter (kWh/m^2 year)		
South oriented, angle 35° (best position)	45	60
South oriented, angle 90°	30	41
East or West oriented, angle 90°	24	33
North oriented, angle 90°	14	19
Bifacial, both sides, 90°*	38	53

*with "Bifacial" is meant 90° installation where both east and west sides of the modules are exposed to the sun

Table 2.2 - Operating Performance of g2e products and forecasted performance

Glass2energy's product offering is ever improving in terms of performance (as it is possible to deduct from the estimations of the above table) and costs as well as expanding in terms of possible options for customers, also due to the collaboration with industrial and research shareholding companies, such as the façade manufacturers FIBAG (www.fibag.at) and SOTTAS (www.sottas.ch), respectively based in Austria and Switzerland, and multinational manufacturer of precision fabrics Sefar (www.sefar.com). For example, this latter joined forces with glass2energy in order to develop an innovative system to avoid the necessity of stripes in the module configuration and, thus, to increase the active area and to improve the efficiency of g2e's DSC panels, while guaranteeing an even more uniform appearance. Such system is based on the insertion, between the two glass substrates of g2e modules, of extremely fine metallic and synthetic monofilaments that are practically invisible to the naked eye. Such metallic filaments have a very low ohmic resistance and could basically act as invisible charge collectors.

Several applications of g2e's "Energy Glass" have been made and very important projects are expected in the next couple of years. One of the first pilot projects was an indoor installation, as infill elements of an internal vertical divider, of translucent red panels, characterized by "wavy" DSCs, at the airport of Geneva, Switzerland. Actually, g2e is still optimizing products for indoor installations and plans to enter the market with such solutions in 2018, giving priority to product for outdoor applications.

Among the present and future realizations of g2e, two deserve particular mention: the first is the multicolor and luminous façade installed at the Austrian Pavillion at 2015 Expo, in Milan (Photo 29); the second one is the Science Tower in Graz, which is an under construction project to be completed in 2016 in the field of Smart City Graz project.

These important projects and realizations bear witness to the great innovative potential that this young solar technology displays for the transformation of building envelopes into transparent and colorful energy-generators.

Photo 29 - The Sun at the Austrian Pavilion of Milan Expo 2015: multi-color DSC façade, manufactured by g2e and FIBAG, integrated with lighting elements for night-time illumination; *(left)* general view; *(right)* detailed view

In 2009, a new kind of DSC, with an efficiency of 3.8%, was developed by incorporating a thin layer of perovskite crystals on the TiO_2 film, by Miyasaka et al. (2009). However, the the liquid electrolyte had a corrosive effect on the perovskyte layer, thus a new solid-state DSC was developed by substituting the liquid electrolyte with a solid hole conductor. Stability have increased remarkably and efficiencies have quickly risen to certified 20.1% in 2014 (Collavini et al. 2015), with potential to grow further in the next years.

Several companies and research centres active in the field of DSC technology (e.g. Fraunhofer ISE, Dyesol, Solaronix) have been transferring their production concepts to the new area of perovskite solar cells, due to their great potential and their conversion efficiency, which is competitive with that of first-generation.

In 2013, a perovskite solar cell with a "non-sensitized" architecture was proposed by Snaith et al. (2012), and became the core technology of the company OxfordPV, spin-off of the Oxford University, previously focused on Grätzel's technology and co-founded by Henry J. Snaith himself.

The commercialization of PSCs is expected for late 2017, since there are still a lot of hurdles to overcome, regarding especially the scale-up of the technology from lab scale to commercially viable dimensions and the durability of the devices.

However, several reasons, besides the efficiency, seem promising for the future of this technology and are attracting a greater and greater interest from the scientific community. The materials for the cells are abundant and cells can be processed at low temperatures into flexible films that roll off inexpensive equipment (Sivaram, Stranks & Snaith, 2015). Among the advantages of this technology there is also the possibility to obtain a good variety of colors (Photo 30) as well as opaque and more or less transparent films that can be easily incorporated into windows and walls of buildings[22].

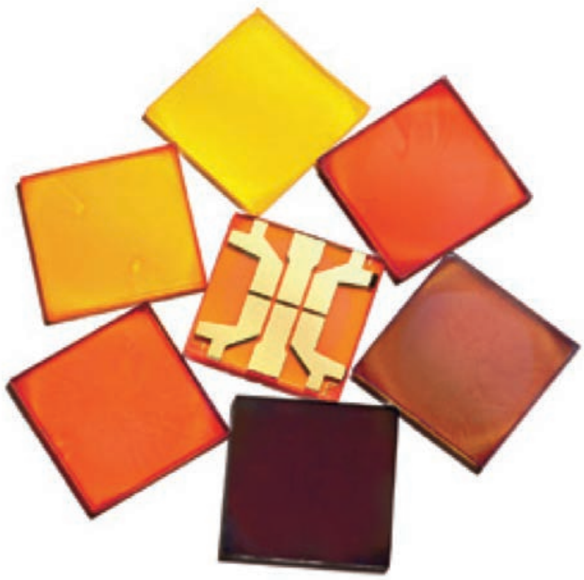


Photo 30 - Different samples of Perovskite Solar Cells (PSC) in a variety of colors

2.3.4. Overview

After having discussed the main, both quantitative and qualitative, parameters that are considered relevant for the integrability of different photovoltaic technologies into buildings, an summary is provided in Table 2.3, where the different parameters are assigned to each PV technology in order to provide a synthetic overview of the above excursus on the design potential of first-, second- and third-generation solar technologies.

			STC performance				Operating performance			Cost		Parameters influencing the Architectural Performance										
			Maximum Cell Efficiency (%)	Module Efficiency (%)	Power Density (W/m²)	Space needed for 1kWp (m²)	Temperature Coefficient, Pmax (%/°C)	Angular dependance	Module Efficiency at lower irradiation	Cost/m²	General Evaluation	Lightness	Transparency	Transparency achievable at the expense of the Active Area	Base Colors	Color variety achievable at the expense of the Efficiency	Uniform appearance at cell level	Uniform appearance at module level	Uniform appearance achievable at the expenses of the efficiency	Bendability	Rigidity/Flexibility of the modules	Peculiarities
1	Mono-crystalline Silicon	mc-Si	24	<20	<200	5-7	-0,45	▼	▼	200	Medium-low	▼	Light-Through	YES	Dark blue/anthracite	YES	YES	NO	YES	Limited	Rigid	Round and/or square (generally with rounded-off angles) wafers, with a uniform appearance, constitute the primary unit of the modules and can be associated in various shapes to provide different results in terms of shapes, transparency and appearance
1	Poly-crystalline Silicon	pc-Si	20	12-18	120-180	6-8	-0,45	▼	▼	120	Medium-low	▼	Light-Through	YES	Shiny blue/ violet	YES	NO	NO	YES	Limited	Rigid	Square wafers, with surface characterized by an irregular grain, constitute the primary unit of the modules and can be associated in various shapes in order to provide different results in terms of shapes, transparency and appearance
2	Amorphous Silicon	a-Si	-	4-6	40-60	17-25	-0,21	◀▶	◀▶	40	Low	▲	See-Through	YES	Brown	YES	YES	YES	NO	High	Rigid/ Flexible	Modules are opaque, continuous and homogeneous films that can be laser-scribed according to different "patterns" in order to achieve different results in terms of shapes, transparency and appearance, in general
2	Micromorph Silicon	µm-Si	-	10	100	10	-0,27	◀▶	◀▶	n.g.	Low	▲	See-Through	YES	Black	YES	YES	YES	NO	High	Rigid/ Flexible	Modules are opaque, continuous and homogeneous films that can be laser-scribed according to different "patterns" in order to achieve different results in terms of shapes, transparency and appearance, in general
2	Copper Indium (Gallium) (di)Selenide	CI(G)S	>20	11-15	110-150	7-9	-0,34	◀▶	◀▶	100	Medium	▲	-	-	Dark grey/ black	YES	YES	YES	NO	High	Rigid/ Flexible	Modules are opaque, continuous and homogeneous films
2	Cadmium Telluride	CdTe	20	14-17	170	6-8	-0,25	◀▶	◀▶	63	Low	▲	-	-	Dark green/ black	YES	YES	YES	NO	High	Rigid/ Flexible	Modules are opaque, continuous and homogeneous films
3	Organic Photovoltaics	OPV	14	-	-	-	-	▲	▲	n.g.	High (being early stage technology) with very low-cost potential	▲	Translucent	NO	Great variety	NO	YES	NO	YES	High	Rigid/ Flexible	Active materials are layers of organic-based materials and compounds, printable according to different designs and/or patterns. Active layers can be characterized by various transparency levels and colours
3	Dye-Sensitized Solar Cells	DSC	15	3-7	30-70	14-33	-0,005	▲	▲	n.g.	High (being early stage technology) with very low-cost potential	▲	Translucent	NO	Great variety	NO	YES	NO	YES	High	Rigid/ Flexible	Active material are layers of hybrid organic/inorganic materials, typically laid down in stripes with non-PV spaces in between but also according to different designs. Active layers can be characterized by various transparency levels and colours

Table 2.3 - Overview of the state-of-the-art analysis of PV technologies in the perspective of the architectural integration, outlining a series of parameters regarding the energy production, architectural, constructional, and economic performance

From Table 2.3 in the previous page, it is evident that first-generation technologies display the highest STC performance and medium-low costs, but at the same time the poorest “architectural” versatility. The highest STC performance implies that is required less PV area for the installation of the same output power. As shown in Figure 2.4, the higher the efficiency, the lower the required space for the attainment of the same power: for example, 5-9 m^2 of crystalline silicon panels are generally needed for 1kWp of PV power, whereas the other generations need notably higher amount of space for the same power to be installed due to the lower efficiency range.

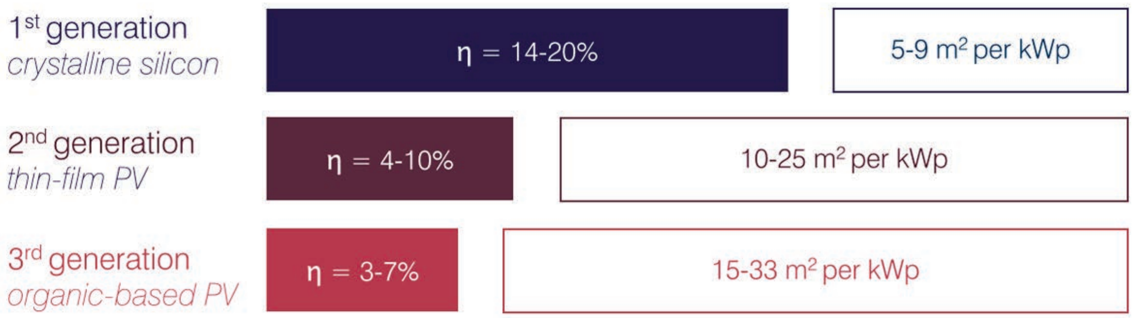


Figure 2.4 - The relation between the efficiency and the space requirement of the different PV generations

As already underlined, however, especially in the BIPV segment, the choice of a solar technology rather than another is subordinated to a series of considerations, that in most cases overlook efficiency. As an example, one can look at the distribution of the different technologies in the BIPV segment and in the PV market, provided in Figure 2.5.

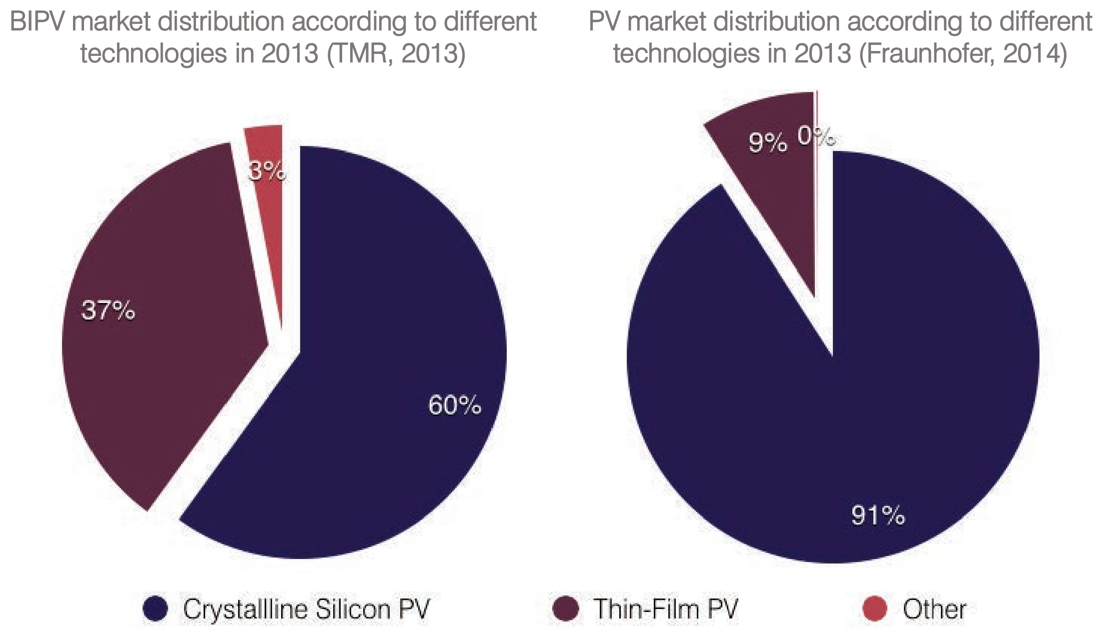


Figure 2.5 - Market distribution of different PV technologies: comparison between PV and BIPV markets

From this comparison, it is possible to see how, for example, market share for thin-film is far more important, in percentage, in the first pie (37%) than in the second (9%), although in both cases crystalline silicon is the most widespread PV technology. This is due to the already discussed parameters that justify preferring, despite the lower nominal efficiency values, second-generation to first-generation technologies, in many building-integrated cases, for one or more of the following reasons:

- better operating performance in case of installation conditions that are not the STC (non-ventilated application, vertical installation, north east or west orientations, possible shading effects and so on…);
- necessity of particular properties, such as flexibility of the modules;
- higher versatility in terms of architectural performance (e.g. more uniform appearance, wider choice in colors).

From the above points, it is clear how third-generation PV technologies, despite of the lower efficiency, have the potential to become more and more relevant as well as competitive presence in the BIPV market, also thanks to the potentially great customizability in terms of color, transparency and design, all features that can be easily tuned according to different requirements. In the previous two generations, it can be noted that a particular color and/or aesthetic effect can be achieved by intervening on the formal characteristics of the backing material, of the cover glass or polymer or either on the thickness and nature of the anti-reflection coating. The solar layer itself basically has a "standard" appearance and, in general, most of the operations that are aimed at modifying the "standard" appearance imply a more or less notable decrease in the performance (e.g. colored glass substrates may imply higher temperatures on modules compared to clear glass, different thicknesses in the anti-reflective coating, which in the best performing case generates the typical blue-violet color of the silicon wafers, results in different colors but in lower energy-harvesting performance, and so on…). Similarly, if some semitransparency in modules is required, the efficiency of both first- and second-generation technologies goes down because some active area must be subtracted, as exemplified in Figure 2.6 for crystalline silicon technologies.

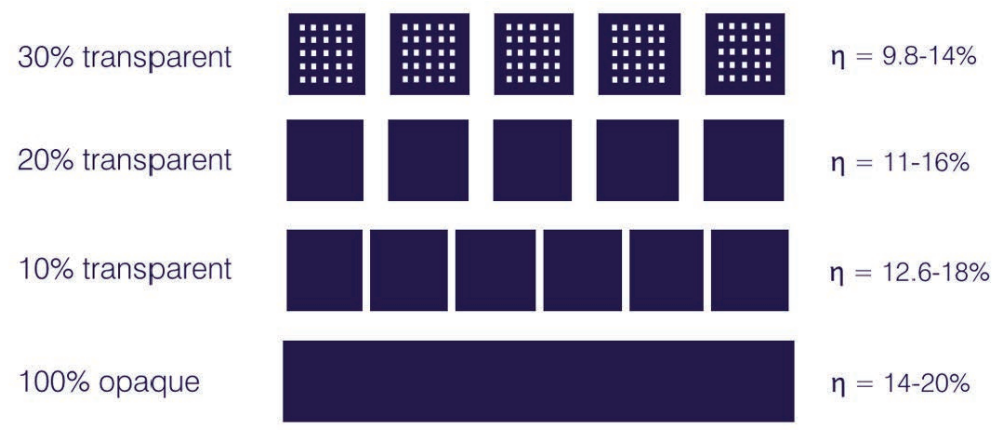


Figure 2.6 - The direct relation between the transparency and the resulting efficiency of first-generation technologies

The great novelty introduced by third-generation technologies, opening further possibilities of research and development, is related to the fact that, in these cases, the solar active layers can be modified and designed nano-structurally as well as easily processed through printing-based methodologies, in order to provide the final products with a certain shade of color, degree of transparency or either a particular drawing. This is an advantage that can not be found in any of the other PV technologies and it is the reason why many see in these technologies interesting potentialities to transform the solar industry.

2.4. Technical-constructional role of PV in buildings

In principle, photovoltaics may find place essentially in any area of the building that is exposed to direct sunlight.

Referring to the technological breakdown of the building fabric described in *ISO 6241:1984, Design of Building systems - Building System and Performance Approach,* the sub-systems that can be involved in the photovoltaic integration, are the following (Table 2.4):

- *External envelope*, whose function is to shape building internal environment and separate it from the outside environment; more specifically, PV can be integrated into the side envelope (façades and windows) and/or the top envelope (roof and sky-lights);
- *Spatial dividers outside the envelope*, whose function is to shape the external spaces linked to the building and separate them among each other; more specifically, PV can be integrated into external horizontal dividers (canopies, porch roofs, etc.) and external vertical dividers (parapets, partition walls).

Sub-system	Examples of assemblies or components	
External Envelope	Top Envelope	Roof
		Roof-light
	Side Envelope	Façade
		Window
Spatial Dividers outside the Envelope	External Vertical Divider	Parapet
		Wall
	External Horizontal Divider	Canopy

Table 2.4 - Sub-systems of the Building Fabric and examples of assemblies or components (according to ISO 6241) that can be involved by the PV integration

For the sake of completeness, also the technological breakdown structure individuated in the Italian Standard *UNI 8290:1981/Edilizia residenziale. Sistemi Tecnologici* is reported, where the following three-level breakdown structure of building technological system is provided (Table 2.5):

- *Classi di unità tecnologiche*;
- *Unità tecnologiche*;
- *Classi di elementi tecnici*, further sub-dividable into functional elements and/or layers.

Classi di unità tecnologiche	Unità tecnologiche	Classi di elementi tecnici
Chiusura	Chiusura superiore	Copertura
		Infisso esterno orizzontale
	Chiusura verticale	Parete perimetrale verticale
		Infisso esterno verticale
Partizioni Esterne	Partizioni esterne verticali	Elemento di protezione
		Elemento di separazione
	Partizioni esterne orizzontali	Elemento di protezione superiore

Table 2.5 - Elements of the building sub-systems (according to Italian Standard UNI 8290) that can be the involved by the PV integration

This breakdown structure of the building system, based on the Performance Approach, is helpful to identify accurately what is the technological function of the single components and to individuate the performance that the components need to supply according to the basic requirements for construction works expressed in CPR 305/2011.

Besides the two above-mentioned technological sub-systems (i.e. classi di unità tecnologiche), also the one related to the external equipment, whose function is to enable or facilitate users' activities in the external spaces linked to the building, can be interested by the PV installation.

It should be also noted that several research works are also exploring the possibilities related to the integration of PV for indoor applications, involving in particular materials and technologies for the construction of energy-generating internal dividers.

In this context, the difference between BIPV and BAPV becomes even clearer. In the case of BIPV systems, BIPV systems are part of the involved sub-system (envelope or spatial divider) as well as of the sub-system entailing the power supply plants. In BAPV systems, solar modules are connected to the surfaces of the envelope or of the spatial dividers, but they only provide electricity production and therefore belong only to the sub-system entailing the power supply plants. From the constructional point of view, besides this more "conventional" *addition* of solar modules on top of the already finished building external surfaces, BIPV elements can be used to integrally replace building envelope components and all related sub-components and/or substitute one or more of its functional layers. In these cases, Weller et al. (2010) talked about *integration* and *substitution*, respectively. In order to exemplify this distinction, three possible solutions for façades are included in the Table 2.6, in the following page.

This performance-based approach turns out quite helpful when "designing" with photovoltaics, in order to understand the requirements that the solar modules need to fulfill and look for the product fit for the given application. A rich toolbox of solutions has been and is being developed in the field of BIPV industry, through the collaboration of the solar and construction sectors, in order to respond to a wider and wider variety of requirements, and it will be discussed in the following paragraphs.

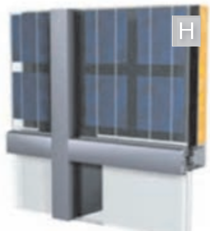
BAPV addition	BIPV substitution	BIPV integration
 A  B	 C  D  E	 F  G  H
Solar panels are added on top of the already finished building skin; they do not provide any additional building function, as defined in CPR 305/2011	BIPV solutions can replace the outer functional layer (generally called to supply weather-proofing and finishing) of building façades. Commercial solutions in general are provided with their own supporting systems, while other layers and components provide the other functions of the façade (insulation e.g. through an air cavity, mechanical resistance e.g. through additional glass panes, etc.)	BIPV solutions can integrally replace façade components, coupled with the appropriate sub-components (supporting structure) and layers for the supply of other functions (e.g. insulation, mechanical resistance, etc.)
A - Example of façade-added solar PV on the south Façade of the "Suglio" Bank Institute (GSE, 2007)	C,D - Example of BIPV ventilated façade, installed in IFT Rosenheim, where solar panels and support structures are provided by Schüco (schueco.com)	F, G - Example of "integral" BIPV façade, provided by Sapa Building Solar and installed in the "Living Tomorrow" building in Brussels (sapa-solar.com)
B - Technical detail of the support structure and of its anchorage to the façade of the building, already finished with plaster (GSE, 2007)	E - 3D render of the Schüco ventilated façades in the SCC series with the Schüco Façade Modules (www.schueco.com)	H - 3D render of the Sapa Solar Opaque solution, indicating the whole stratification of the provided system and showing its integrabilty with transparent glass panes (sapa-solar.com)

Table 2.6 - Three of the possible applications of PV modules on the façade of a building

2.4.1. Solutions for the Top Envelope

The main part of building-mounted PV installations regards roof-top solutions, mainly due to the higher related solar yields in both sloped, sub-horizontal and/or horizontal surfaces, compared to vertical installations. For example, as seen in Chapter 1, in horizontal (tilt=0°) installations, only 10% drop in the solar yield is registered compared to the "optimal" installation (i.e., in Central Europe, facing south with 30° tilt). This drop is more important in vertical installation conditions (20-30%).

Several possible options may be individuated:

- *specific solutions for flat roofs*, further subdivided into:
  - stand-off systems;
  - PV-integrated weatherproofing layers (flexible roof sheeting);
- *specific solutions for pitched*[23] *roofs*, further subdivided into:
  - stand-off systems;
  - PV-integrated weatherproofing layers (solar roof tiles);
- *specific solutions for saw-tooth roofs*;
- *other solutions for roof-integrated PV*:
  - PV-integrated cladding layers;
  - PV-integrated translucent and/or opaque "integral" systems.

2.4.1.1. Specific solutions for flat roofs

Despite all the benefits regarding multifunctional BIPV solutions, still one of the most frequently encountered types of installation of PV systems on flat roofs is building-added stand-off systems: indeed, they represent a low-cost approach, able to achieve optimal installation angles; but, at the same time, they are often considered impairing the architectural language of buildings so that, in several cases, the adopted strategy consists in hiding them behind peripheral roof-top walls (see Figure 3.2, p.106).

Stand-off solutions are characterized by the presence of metal support structure that allows for the installation of the modules according to the required angle as well as their rear ventilation. The supporting structure can either be permanently fixed to the top envelope structure or be a free-standing structure laid on the weatherproofing layer of the roof and held in place by means of additional ballast (such as concrete paving slabs, plinths and/or gravel-filled metal sheeting). In both cases, it is important that the weatherproofing performance of the roof is not compromised by the PV installation. Planners, in retrofit interventions, must verify that the structural capacity of the roof is not compromised by the PV installation and, in new constructions, they must consider the weigh of the PV system, when dimensioning the load bearing structure of the building and, in particular, of the roof. The fixed anchorage system is preferable in new constructions, while in retrofit solutions a less invasive free-standing system could be the best option.

In stand-off systems, modules are organized in rows that need to be distanced among each others in order to avoid reciprocal shading. This obviously leads to the impossibility to fully cover the roof surface with solar panels, which is a downside not to underestimate.

A widespread (and quite "standard") solutions for integrating PV on flat roofs — enabling to maximize the surface covered in solar modules, to reduce the weight of the installation, to avoid all the additional construction works related to stand-off solutions and related technical elements (e.g. support structure) — consists in the use of flexible PV-integrated roof sheeting as weatherproofing layer of the roof (Figure 2.7). Such multifunctional products are very lightweight thin-film modules (typically, in amorphous silicon) on flexible plastic substrates; compared to stand-off systems, this solution is characterized by worse installation angles and higher temperature of the modules (due to the absence of rear ventilation), but the use of amorphous silicon, that is characterized by relatively good temperature coefficient and low dependance on the installation angles compared to crystalline silicon technologies, and the other above-mentioned advantages, help reduce the relevance of such inconveniences. Also roofs with more complex shapes (e.g. barrel vaults) can be made PV by using such flexible BIPV sheeting solutions, as regards both new construction and retrofit interventions.

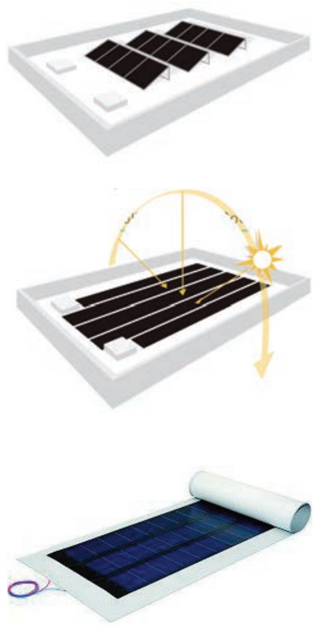


Figure 2.7 - *(top, middle)* Comparison between stand-off system and flat installation of PV-integrated weather-proofing sheet (www.globalsolar.com); *(bottom)* Solar PV roof membrane (alwitra-EVALON®)

2.4.1.2. Specific solutions for pitched roofs

Pitched roofs are already slightly tilted with respect to the horizontal and, especially when south-oriented, they can be (and, indeed, have been most commonly) considered the best places where to put PV modules, due to the significant solar yields. At the same time, compared to flat roofs, they can be way more visible and thus the installation of PV can have a non-negligible impact on the appearance of the building. Because of this, a multiplicity of solutions for both added stand-off and integrated systems has been developed as well.

As for stand-off systems, it is important to note the presence of a metal support structure, mounted on top of the finished roof, slightly distanced from it to allow for modules rear ventilation and characterized by three main subcomponents: roof anchorage, mounting rails, module fixing. These sub-components are produced in a great variety of shapes and characteristics, since they have to adapt to the great variety of existing technical solutions for pitched roofs.

One of the most widespread (as well as rather conventional) solutions for integrating PV on pitched roofs is related to the so-called "solar roof tiles", which have found significant applicability especially in the energy retrofit segment, due to their high integrability with conventional solutions for roof-covering. In particular, a large variety of colors, shapes, configurations, mounting systems, substrates have been developed in order to respond also to the great variety of tiles depending on local technical traditions and materials availability.

2.4.1.3. Specific solutions for saw-tooth roofs

Saw-tooth roofs are particularly interesting locations for the integration of solar modules, with a great applicability potential in both new construction and retrofit segments, due to their conformation that is useful to provide an adequate balance between PV production and daylighting. In particular, this type of roof allows — when appropriately designed — exploiting two different orientations: the south-exposed side, to integrate of more or less opaque solar modules, which can be tilted in order to optimize the energy harvesting of the system; the north-exposed side, to optimize visual comfort conditions by letting in diffuse daylight and provide natural ventilation. Some BIPV manufacturers (e.g. the Sicilian Coversun, within the Cappello Alluminio Group[24]) have developed standardized prefabricated solutions, which result particularly promising also in the field of the renovation of industrial buildings (Photo 31).

Photo 31 - Prefabricated modules for saw-tooth roof manufactured by Coversun, Cappello Group

Photo 32 - Open saw-tooth roof at Ludesch Town Hall, 2006: on the right, detail of the 3-way division of panels

This should not be confused with the installation of more or less “standard” panels according to the shape of saw-tooth roof, a practice that occurred in several buildings (see for example Photo 32). De facto, the arrangement of the panels like a saw-tooth roof could also be a useful strategy to increase the area of the solar system and to optimize the inclination of the PV surfaces with respect to the flat 0° installation; however, the possibility of self-shading occurring between contiguous sheds must be carefully considered, since it can generate malfunctioning in the system and impair its efficiency.

For example, in the Local government offices in Ludesch, by Herman Kaufmann (2006), the semi-transparent monocrystalline silicon panels, installed as infill elements of the saw-tooth horizontal divider covering the square in front of the building, had to be subdivided into three different electrical zones (Weller et al. 2010):

- the bottom rows, which are always in shade and, therefore, are not connected to the electrical installation;
- the middle rows, which are shaded in winter due to the low sun angles and to the snow;
- the top rows, which are never in shade and are connected separately in order not to see their efficiency conditioned by that of the middle rows, which have a less advantaged position and thus are characterized by lower energy harvesting.

2.4.1.4. Other roof-integrated PV solutions

Besides roof tiles and flexible sheeting, other solutions have been developed for the realization of *PV-integrated cladding layers*, in the form of more or less standardized panels (on glass, metal and/or plastic substrates) that can be framed or frameless. Where possible, especially for roof-top installations, planners should take into account the problems related to modules overheating and provide the modules of a rear ventilation cavity[25] (cold roof), even if some PV technologies of second- and third-generations, as already underlined, do not suffer overheating as much as first-generation technologies.

In parallel, several *translucent and/or opaque "integral" systems* (as in the definition of Table 2.6) were developed and widely applied to fully substitute the top envelope with one single solution that, besides generating clean electricity, is called to fulfill all functions that are typically provided by two or more components of the building envelope.

Several products, for example, result from the integration of flexible thin-film modules with metal sheets in order to obtain very lightweight metal-based products, in different shapes, for the construction of roof cladding; where necessary, the metal element itself is provided with a more or less thick layer of insulating material and therefore, with the all necessary subcomponents and the appropriate supporting structure, can integrally substitute the top envelope. These solutions have found widespread application in the field of industrial building roof-top cladding, also thanks to their lightweight as well as resistant nature that also allow covering wide spans. In this field, one can cite as an example the Italian company Ondulit s.p.a., which has partnered with the amorphous silicon modules manufacturer Uni-Solar to provide a line of BIPV products called Enercover®: this line consists of multilayer protected steel roof panels integrated with thin-film modules on metal sheet substrate (Photo 33). The cavity between the solar modules and the insulation layers below is ventilated and this increase the operating performance of the modules (Figure 2.9). The lightness and flexibility of the modules and the wide range of accessories for the installation allow for a great aesthetic and functional integrability on both curved and planar roofs, in both retrofit and new construction works. One of the most famous applications of this product has been in the commercial and residential building in Gallarate by Mario Botta (Photo 34).

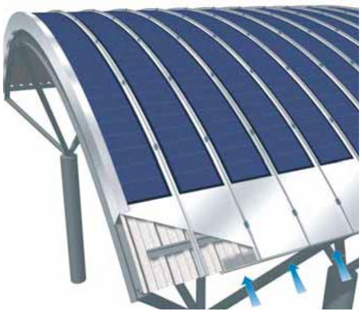


Figure 2.8 - Functioning scheme of Enercover Top (www.enercover.it)

Photo 33 - Close view of Enercover installed as roof cladding

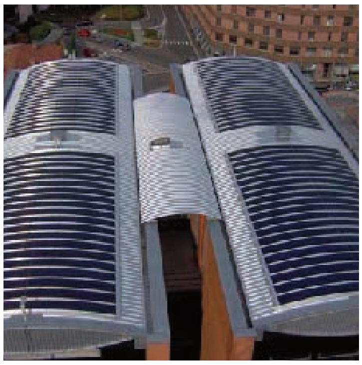


Photo 34 - Commercial-residential building, Gallarate, M. Botta, 2010

In the category of PV products integrated as cladding layers of roofs, it should also be mentioned the emergence of a new series of products for the realization of the finishing layer of walkable PV-integrated floors, further widening the possibilities of the PV technology for the architectural integration in buildings. For example, the Spanish company Onyx Solar, specialized in glass solutions for building integration, has developed a line of walkable PV panels (Photo 35), complying with the anti-slip regulation thanks to their "irregular" surface finishing and supporting 400kg point load. These modules are provided in a wide range of colours and can even be translucent and rear-illuminated thanks to the integration with LED.

As regards, the translucent glass-based "integral" solutions, they are not relevantly different from those designed for the side envelope (that are going to be discussed more in detail in the following paragraph), but it is important to underline that, when we are in front of a roof integration, special requirements could emerge, so that a product for façade integration could not be adapted. For example, such requirements could be related e.g. to the walkability of a translucent PV roof (e.g. for maintenance) for which special performance in terms of mechanical strength as well as resistance to abrasion are required. Another fundamental aspect to take into account is related to the safety requirements in case of glass breakage; therefore, glass-based BIPV modules should foresee the use of laminated safety glass, avoiding the danger related to large fragments of glass falling on the areas below.

A special translucent "integral" solution, which has already found its first applications, is represented by the PV-integrated ETFE cushions, allowing for the attainment of semitransparent and high-insulating PV envelope with one single installation. For example, 220 triple-layer ETFE pneumatic cushions integrated with thin-film solar cells were used to cover the roof of the AWM Carport in Monaco (Photo 36). The cells (12 for each cushion) are fixed mechanically to the middle layer; the inner ETFE film is printed to reduce the light transmitted and avoid thermal and visual discomfort below the roof; the upper film is fixed separately from the other two below, so that the substitution of eventual faulty modules is feasible. The air supply, inflating the cushions, is connected to the lower chamber and air is exchanged with the upper chamber via overflow openings in the middle film layer (Corne, 2011). This 9,600 m^2 roof was developed by Tanyo Europe GmbH and MakMax Group and is expected to produce 130 MWh/year[26].

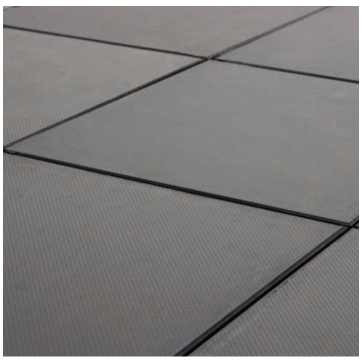


Photo 35 - Close view of the Walkable PV floor by Onyx Solar

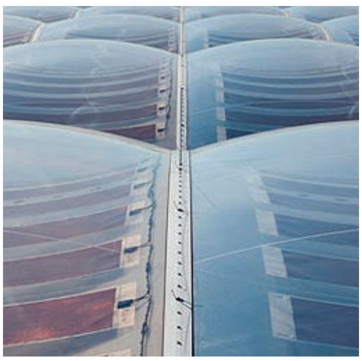


Photo 36 - AMW Carport roof, Ackermann&Partner, Munich, 2011: detail

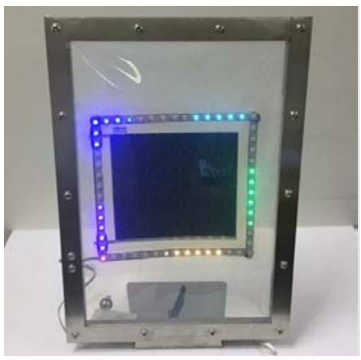


Photo 37 - Prototype of ETFE-MFM, presented at 2014 Energy Forum

In this field, it is of relevance to mention the ETFE-MFM project (within the European Union 7th Framework Programme) started in 2014 and aimed at the development and demonstration of multifunctional PV- and LED-integrated ETFE modules for architectural façade lighting. Among the ETFE-MFM partners, besides the above-introduced Tanyo Europe, the German manufacturer of flexible CIGS modules Solarion is involved for the provision of customized elements to be integrated inside the cushions. Cushions will be installed and monitored in the chosen demonstration site: the headquarters of the project leader, the research centre ITMA, in Spain. The first mock-up of this technology (Photo 37) has been presented in 2014 at the Energy Forum in Bressanone.

In addition, it is also interesting to refer to Hua et al. (2014), where a three-layer ETFE cushion structure integrated with a-Si solar modules is proposed and tested experimentally: the results of the test demonstrate the feasibility of the solution proposed to self-sustain cushion operation through PV and to provide a way of collecting thermal energy as well.

2.4.2. Solutions for the Side Envelope

Although vertical surfaces are not ideal in terms of orientation and thus are associated with lower yields, when PV elements also provide other technical functions, these disadvantages can be compensated. Moreover, one should also think about the great unused potential for solar energy harvesting and electricity production of vertical sun-exposed building surfaces, which offer to designers and builders millions of square meters of surfaces potentially active for clean electricity production. Last but not least, the architectural integration of PV introduces new and important possibilities also at the level of the architectural language, with all related “symbolic” values that often make active solar façades perfect bearers of the message of sustainability and technology that is commonly acknowledged to photovoltaic technology. Indeed, for obvious reasons, façade-integrated solutions are in general more “visible”, compared to most of roof-integrated solutions.

Besides the façade-integrated solutions, PV modules can also be building-integrated into the side envelope as components for windows.

2.4.2.1. Solutions for Façades

Speaking about active solar façades, PV products may be installed as functional layers and/or elements according to different options, which obviously imply a change in the performance that the BIPV products need to fulfill.

The main options are the following:

- *Cold façades systems:*
  - Cladding elements of ventilated façades;
  - Outer layer of double-leaf façades;
- *Warm façade systems* (“integral” systems);
- *External sun-shading devices*;
- *Stand-off systems*.

The integration of solar modules as *cladding elements of ventilated façades* has found several applications in new constructions, but it can also be quite easily implemented in the field of energy retrofit interventions. In those solution, the modules constitute the weather protection of the façade as well as its finishing layer, separated from the thermal insulation layer from a ventilated air cavity (which, besides dissipating any condensation and water vapor collected, may also help avoid an excessive overheating of the modules). Framed and/or frameless modules are fixed, by means of either linear (Photo 38) or point (Photo 39) supports, to a supporting structure, which is in turn anchored to the load bearing structure of the building and/or to the inner wall.

Modules (e.g. glass-glass, glass-plastic laminates) are commonly opaque solutions since they also are called to conceal the thermal insulation layer. Besides the aesthetic performance, they technically differ from standard PV modules because of the requirements linked to the weatherproofing and structural integrity (e.g. in case of glass-glass modules, heat-soaked toughened safety glass is required according to DIN 18516[27], as pointed by Weller et al. 2010). The junction boxes of the modules and other connection elements can be quite easily hidden on the rear of the panels.

A quite similar solution consists in the integration of BIPV translucent products as the *outer layer of double-leaf façades*; this type of façades (widely discussed in Chapter 1) are characterized by two more or less transparent surfaces separated by a mechanically and/or naturally ventilated buffer space, which is used as an air channel. The air chamber is useful for improving the thermal insulation performance of the whole façade and the air flow helps maintain lower module temperatures. The PV modules constitute the weather protection and finishing layer of the façade — just as in the case of ventilated façade systems —, but here they may also provide the additional function of daylight attenuation. Such solution has find a wide applicability also in the field of the energy retrofit (Photo 40), where the creation of a second sun-exposed glazed skin allows for the increase of the thermal insulation performance of the side envelope as well as for the creation of sun spaces able to regulate passively the energy fluxes between the outdoor and indoor environments, according to the season and to building requirements.

Photo 38 - Milbertshofen cultural centre, 2008: a-Si façade (VOLTARLUX®) with linear supports (Arnold Glas)

Photo 39 - Paul Horn Arena, Tubingen 2004: PV façade in green pc-Si panels (Sunways) with point supports

Photo 40 - NTNU, Trondheim: translucent double-leaf façade, retrofitted in 2000

In both the above-described options that can be referred to as “cold façade” systems, it is possible to exploit passively the heat developed by the modules to optimize the bioclimatic performance of building envelope. Some examples and a more detailed description of the related solutions will be provided in the following chapter (paragraph 3.4.3).

Photovoltaic modules can also be integrated as infill elements of “warm façade” systems, which are single-skin solutions where all envelope functions are fulfilled by the BIPV products themselves (see F-H in Table 2.6, p. 64). They can either be a semi-transparent infill or opaque cladding element. Differently than in the previous two cases, the BIPV products themselves must be provided, where necessary, also of an additional insulating function. Hence, in opaque cladding solutions, a layer of insulating material must be incorporated into the BIPV product. Instead, in translucent glass-based systems higher insulation may be provided by additional panes, eventually treated with specific coatings and separated among them by evacuated and/or gas-filled cavities. Translucent glass-based solutions found a wide applicability also due to the further shading and light-scattering functions, solving a multiplicity of functions with one product and one installation. Differently than the previous “double-layer” options, no additional support structure are required for the modules, since they coincide with those needed for the building envelope construction. On the other hand, the absence of the ventilation cavity can generate high temperatures on the rear of the modules and must be carefully taken into account, in order not to compromise building performance.

As regards the supporting structure (most frequently in steel, aluminum and wood), this does not differ from the existing post-and-rail façade solutions, but in this case it must be provided of the adequate and inspectable housing for electric connections and devices.

A slightly different solution from the above-introduced consist in the installation of solar modules as *external sun-shading devices*, intended as an added functional layer/subcomponent of the façade system. Photovoltaic modules and sun-shading devices are perfect partners, since both can be tilted against direct sunlight in order to provide maximum performance in terms of electricity production and sunlight attenuation respectively. Moreover, a good ventilation is possible thanks to the fact that PV sun-shading elements are physically separated from the other functional layers of the building envelope. This could help further optimize the actual production of the PV system, compared to the translucent, integral solutions discussed above. This aspect has also a downside related to necessity of other subcomponents to be installed on top of the building envelope. This obviously generates higher installation costs, which can be perfectly compensated by the other benefits and the high performance provided.

Two main solutions can be identified:

- *PV-integrated shutters*: vertically-mounted covers for façade openings and/or windows.
- *PV-integrated louvers*: horizontal slats, tilted to admit light and air but keep out direct sunshine.

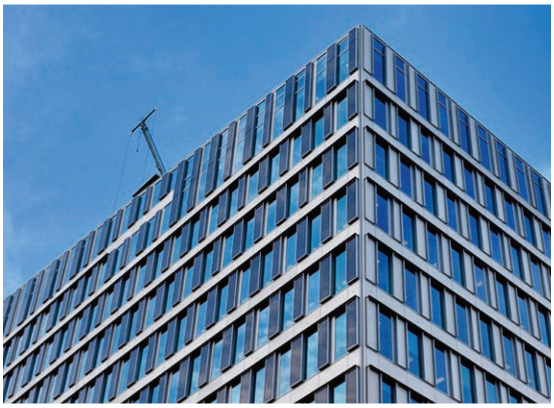


Photo 41 - View of the PV shutters at "The Edge" Deloitte Building, PLP Architects, Amsterdam, 2014

Photo 42 - View of the PV louvers installed in the field of Groenhof Castle, Flanders, Samyn and Partners, 1999

The sun-shading devices can be fixed or movable. Movable systems can either be operated by the users or be activated automatically; the second option obviously implies higher construction, operation and maintenance costs, which are on the other hand — at least, as regards the systems based on PV-integrated louvers — linked with higher solar yields and, in theory, optimal shading performance. Indeed, such solutions basically operate as uniaxial sun-tracking systems.

A correct design as well as a cost-benefit analysis of such solutions must be undertaken in order to verify their effective economical and environmental sustainability, compared with corresponding well-designed fixed options, also given the fact that nearly 50% of average annual radiation is present in the form of diffuse radiation (Krippner, 2003).

On the other hand, fixed systems require lower constructional and operational costs, but also provide lower yields, in particular, as regards the systems based on PV-integrated louvers. In these cases, it is important to individuate the best angle that provides, on an overall balance, the best performance in terms of shading and PV production as well as the correct spacing among louvers, in order to avoid malfunctioning related to self-shading. According the daylight levels required inside the building, the modules used for these kinds of installations can be opaque or semi-transparent in various degrees.

Finally, modules can also be added as *stand-off systems*, i.e. added elements to the already finished side envelope. They should determine positive relapses on the aesthetic performance of the façades, by helping improve the appearance of building, but in many cases they are only added to increase possible surface to expose to the sun without any concern related to their aesthetic performance (see A-B in Table 2.6, p. 64).

2.4.2.2. Solutions for Windows

Solar modules can also be integrated as multifunctional elements and/or layers of windows, the building components of the side envelope allowing the passage of light and, if not closed or sealed, air and sound as well as, in some cases, things and people.

In particular, solar modules can be integrated in windows as:

- *Semi-transparent infill elements* due to their shading and light-scattering properties, they can be used as sunlight attenuation elements in order to optimize visual and thermal indoor comfort; if coupled with other elements for the optimization of the performance related to the requirements related to users' comfort and safety (for example, triple-glazing for better thermal insulation, multi-layer laminates for higher safety).
- *Opaque infill elements* (e.g. spandrel panels, parapets of window systems);
- *Sun-shading subcomponents* (e.g. movable or fixed louvers, foldable or sliding shutters).

A careful choice of colours, reflectivity, and other features of modules and of the framing sub-components is recommended for the solutions to as compatible as possible among each others and with respect to the other building façade materials. The same considerations expressed in par. 2.4.2.1 are also valid here, with the appropriate specifications.

2.4.3. Solutions for Spatial Dividers outside the envelope

As regard the installation of PV as part of spatial dividers outside the envelope, we can distinguish, in general:

- among *Horizontal External Dividers*, solutions aimed at weather protection and/or sunlight attenuation elements such as canopies, shelters and so on;
- among *Vertical External Dividers*, solutions aimed at the protection from falls (such as balcony parapets) as well as external partition elements (such as external walls) that can also provide weather protection (e.g. wind reduction, sunlight attenuation and so on).

Such solutions do not differ significantly with respect to similar solutions for the building envelope (façade parapets, external vertical walls, translucent and/or opaque roofing systems); however, not all requirements coincide because, for example, thermal insulation and/or weatherproofing performance are not required when PV elements are called to separate two external spaces. However, considering e.g. a parapet solution — be it either part of the side envelope or of the external vertical divider — the solar modules integrated need to be strengthened by means of specific subcomponents (i.e. highly resistant substrates and adequately dimensioned support structure) in order to provide the appropriate level of safety for users.

2.5. Online Databases of BIPV products

The above-discussed are the main possibilities for the constructional integration of PV modules in buildings. For more detailed information regarding different products for the integration of PV in architecture, it is possible to refer to the websites of BIPV companies and to specific online databases, which have been elaborated with the aim to gather and structure data regarding different BIPV products. In particular, it is worth to mention the database about *innovative solar products for building integration* (2014)[28], elaborated, in the field of the Task 41 "Solar Energy and Architecture" of the IEA-SHC programme, by the Laboratoire d'Energie solaire et de Physique du Bâtiment (LESO-PB) of the EPFL. Within this database, where also solar thermal and hybrid PV-ST technologies are accounted for, products can be selected according to the PV technology (monocrystalline, polycrystalline, or thin-film) and the "position on building" (pitched roof, flat roof, skylight, opaque façade, translucent façade, shading). Each product is provided of a sheet with a description containing name of the manufacturer, technical details as well as some consideration regarding the appearance of the products. Moreover, each product "integrability" is assessed according to a series of parameters that regard the multifunctionality of the element, its flexibility in terms of shape and size, the choice offered in terms of both colors and patterns. Another aspect that is evaluated is the availability of "dummies" i.e. of not active elements that can be used to maintain modules appearance unvaried also in totally or partially shaded areas, where putting a PV module would generate malfunctioning in the system. Moreover, the assessment of the product also regards the availability of options for jointing/frame and of a complete construction system. Where available, technical details are provided along with photos of built examples where the given product is installed.

In addition, it is also of relevance to mention the online database of products and fastening systems, elaborated by Swiss Competence Centre on BiPV within the Istituto di Sostenibilità applicata all'Ambiente costruito (ISAAC)[29]. This database is focused on multi-functional BIPV products (catalogued according to their function) as well as on fastening systems (classified based on whether they are used for roof, façades, or shading devices). Products can be also added on request by the manufacturer themselves.

2.6. New Research Branches and Developments in the BIPV sector

Nowadays, the cost of solar modules and their efficiency are still important targets in the field of PV market, but they do not represent relevant hurdles as before; de facto, the technical progresses as well as the maturity reached by the PV market have allowed to scale these issues down and, especially in the BIPV sector, a series of new objectives have emerged and are being specifically targeted. In particular, these research developments are more and more oriented towards the maximization of the aesthetic versatility of the products and, also due to the great novelties introduced by third-generation technologies, are widening significantly the applicability of PV in architecture in many contexts otherwise difficult to be targeted.

In many cases, these developments move from the necessity to meet some specific architectural requirements, which could be more or less directly expressed by architects and customers of the BIPV market and which, otherwise, would not be fully met with any of the existing solutions. This has often implied a certain increase in cost and a decrease in the efficiency of the devices compared to more or less standard PV solutions; nevertheless, these aspects can be compensated by the unique architectural features achieved and, keeping costs within a certain range, can make BIPV products highly-competitive compared to the corresponding "non-active" building solutions.

Having said that the following characteristics have been individuated among the new research developments of the BIPV sector: luminescence of devices, maximized light transparency, appearance imitative of other materials, indoor integrability, etc. These are discussed in the following paragraphs.

2.6.1. Luminescent Solar Concentrators

A luminescent solar concentrator (LSC) is a device that uses a thin transparent sheet doped with luminescent species, to trap solar radiation over a large area and redirect it (through luminescent emission at longer wavelengths) to cells mounted on the edges of the material layer (Figure 2.9). The thin sheet typically consists of a polymer, such as polymethylmethacrylate (PMMA) or polycarbonate, or glass waveguide and the luminescent species, which are either embedded in the waveguide or applied as a separate layer on top or bottom of it, can be organic dyes, quantum dots or rare earth complexes.

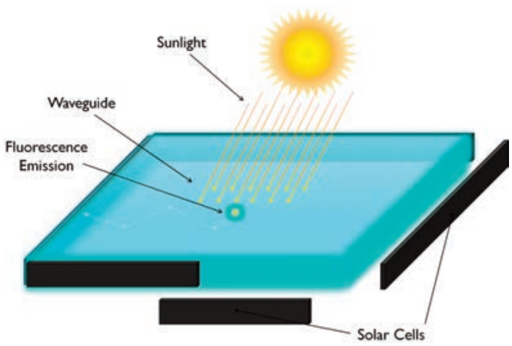


Figure 2.9 - Scheme of the layout and of the functioning of a Luminescent Solar Concentrator, LSC (www.samwilton.com, 2012)

LSCs offer potentially lower costs, since they avoid to cover large areas with silicon (or other) solar cells, which are disposed at the edges of the material layer, where they receive and convert effectively both the direct and diffuse solar radiation striking on the surface of the device and concentrated. Another advantage of this technology might be linked to the possibility to use LSCs independently from the orientation or inclination of the surface with respect to the sun, thus promising a certain freedom for integration in urban environments compared to the traditional PV systems[30]. Hence, LSCs turn out to be excellent candidates for BIPV and, in particular, for the cloudier northern European countries[31].

On the other hand, the "peripheral" position of the cells obviously implies a smaller PV area and related power output. As regards, in particular, the conversion efficiency, the best values in LSC devices to date remain within 2–4% range, if using crystalline silicon cells[32].

The appearance of the devices depends on the characteristics of the materials used and, in particular, of the luminescent element (typically a dye) which may influence the final color and the optical transparency. Lightweight and flexible LSC devices can also be manufactured, boosting the design potential of this technology.

Due to their colorful and fluorescent appearance (Photo 43), LSCs have an interesting potential for BIPV, despite the small efficiency; however, their fluorescence might in some cases limit their applicability. The issues regarding the acceptance and the applicability of LSCs are the object of dedicated studies, aimed to identify possible targets of this technology in terms of building products and design solutions. For example, the 3TU.Bouw Center of Excellence for the Built Environment (joint initiative of the three universities of technology in the Netherlands) is developing a research on LSCs, specifically targeted to explore their applicability potential for the integration in the built environment as well as the aspects related to their manufacturing and integrability into specific products. All that is pursued by adopting a participatory approach, involving different stakeholders (in co-creative workshops, interviews with experts and an open innovation surveys) to gather various ideas about LSC applicability[33].

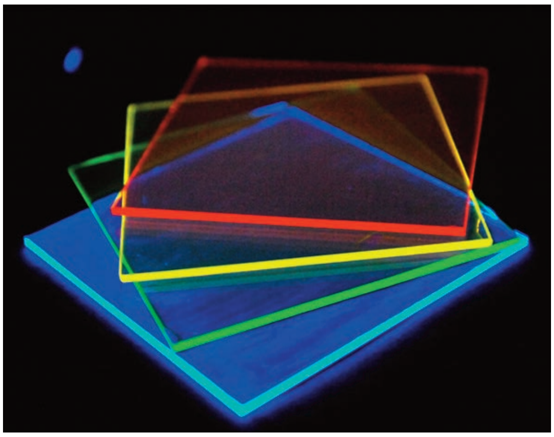


Photo 43 - Luminescent Solar Concentrators (LSCs) developed at Massachussets Institute of Technology in different colors

Photo 44 - Shelter for recharging electric bycicles integrated with yellow LSCs at the Division Refining & Marketing of Eni, Rome

In parallel, several research efforts address the optimization of the stability and efficiency of the devices, with particular regards to the luminescent species, and the competitiveness of the LSC devices, especially in terms of cost.

An example of LSCs application into an urban context, able to display also their aesthetic potential, is the pilot installation of a PV shelter for the parking of electric bicycles at the Division Refining & Marketing of Eni Headquarters, Rome, in November 2012 (Photo 44). The 60-m^2 installation of 192 photo-active yellow sheets, based on LSC technology, is able to generate approximately 500 Wp for the recharging of the bicycles[34]. The system was installed with the purpose to study and monitor the real operating behavior of LSC technology and, in particular, of the devices developed and patented by Eni, in order to optimize their performance accordingly.

2.6.2. Light-transparent Photovoltaics

An important direction of research in the field of BIPV regards the study and development of semi-transparent PV for the construction of lightweight, energy-saving and producing building envelopes.

Besides the already-mentioned *Light-through* and *See-through* solutions, defined in Baum, 2011, and regarding essentially first- and second-generation technologies, plenty of progresses have been done for the development of novel solutions aimed at maximizing the light transmission of PV, while trying to compromise the least the electrical performance of the devices.

As already underlined, third-generation solar technologies opened new scenarios in this direction. Indeed, in these cases, it is possible to talk about *Translucent* solutions: in these cases, the active surfaces can indeed be semi-transparent in various degrees, letting a portion of the visible light cross them, while absorbing the remaining part (unless of the reflected part that of course should be reduced to the minimum).

In this regard, it should be noted that most of the energy of the sun's spectrum belongs to the visible range (i.e. that part of the spectrum that is perceived as light by the human eye and comprised between 280-780nm wavelengths)[35]. Thus, in principle, opaque devices are the best performing as regards the power output. However, in the field of the architectural integration, higher degrees of transparency might be required e.g. for reasons related to visual and thermal comfort requirements and might lead, on an overall balance, to a better performance of the building (as it will be widely discussed later in this work, with the support of plenty of literature studies and examples).

It has already been highlighted the target 50% transparency of the OPV company Heliatek (Figure 2.3, p. 50); several attempts have been made both at optimising the transparency and electrical performance of DSCs for building-integrated photovoltaic (BIPV) roofs and facades (e.g. Halme et al. 2012). Perfectly in line with this trend, a recent development in the field of BIPV industry has led to the development of *Transparent* solutions, fundamentally aimed at making the PV technology invisible to the human eye. Such solutions are characterized by highly transparent as well as colorless surfaces, able to convert solar energy into electricity. In this field, it is worth to mention, for example, the development, by the Japanese company TDK, of a white-colored DSC with a specific dye that absorbs only in the NIR range (Kalyanasundaram, 2009), which is a wavelength range that is not perceived by the human eye. In addition, it is useful to cite also the activities of two startup companies that addressed this concept of "invisible photovoltaics" through two different approaches, which are provided as follows:

- ClearVue PV (www.clearvuepv.com), based on Luminescent Solar Concentrator (LSC);
- Ubiquitious Energy (http://ubiquitous.energy), based on IR- and UV-absorbing OPVs.

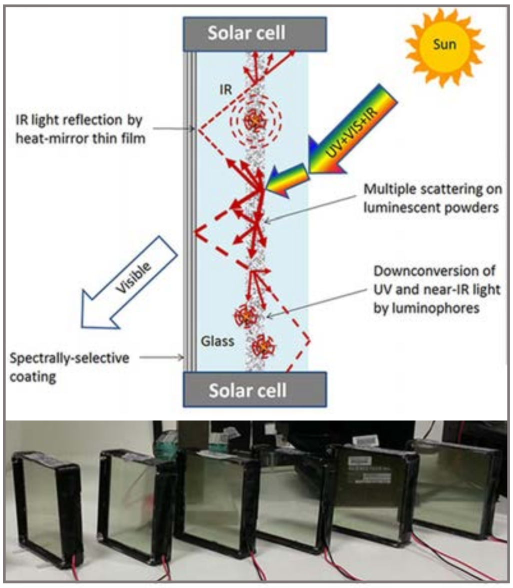


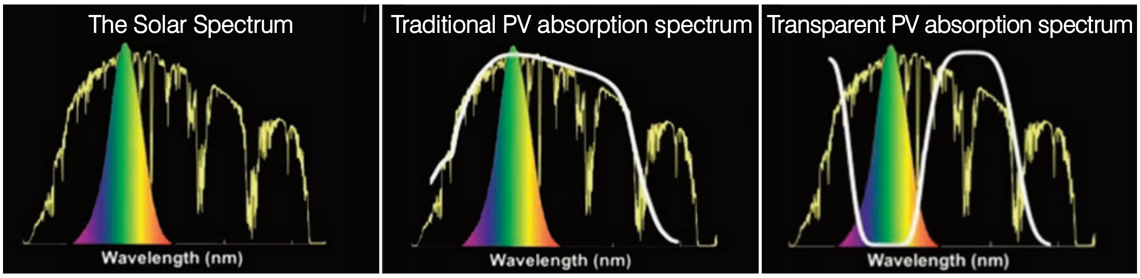
Figure 2.10 - Scheme of the functioning of the technology of ClearVue PV and photo of some prototypes (Alghamedi et al., 2014)

Founded in 2015 in Australia, ClearVue PV has developed an advanced glazing technology able to produce electricity from UV and IR solar energy, while transmitting most of the visible solar radiation. In particular, as shown in Figure 2.10, it is a clear glass structure made of two low-iron flat glasses, with a spectrally-selective coating on the back surface (reflecting the IR radiation and letting visible light through) and a luminescent interlayer containing inorganic luminophores. The interlayer, besides keeping the two panes together, provides photo-induced re-emission of the absorbed photons and redirects them towards the edges of the glazing, where a solar cell (a CIS cell in the prototype analysed in Alghamedi et al. 2014) converts them into electricity, acting like a "hybrid" solar concentrator[36]. The company has already executed several tests and intends to commercialize a product range suitable for commercial distribution already in 2016. In September 2015, a 50x50 cm 75%-transparent window prototype has been presented with 8 Wp output power.

A different approach for the achievement of highly transparent PV devices, has been carried out by the American company Ubiquitous Energy also founded in 2015. The company's patented technology, ClearView Power™, consists in near-IR and UV absorbing organic photovoltaics (OPVs), combined with selective high-reflectivity near-infrared mirror coatings. The first prototypes displayed around 2% and a transparency of over 55% (Lunt & Bulovic, 2011), but the aim of the company, spun-out of the Michigan State University, is to reach 90% transparency and up to 10% efficiency in the next future. Ubiquitous Energy solar devices selectively transmit the light visible to the human eye while absorbing only the ultraviolet and infrared light and converting it into electricity (Figure 2.11), allowing any surfaces to convert ambient light into electricity without impacting their appearance. The company has already established prototyping and pilot production capabilities for the production of a highly-transparent film to be applied, firstly, in mobile application and, in a second phase, as coating for architectural glass.

Photo 45 - Prototype of transparent solar cell according to Ubiquitous Energy technology

Figure 2.11 - *(from left to right)* Solar spectrum distribution in function of the wavelength, with indication of the human eye response; Spectral absorption of traditional PV; Spectral absorption of Ubiquitous Energy transparent PV (Barr, 2014)



To conclude this excursus regarding light-transparent PV technologies for energy-saving and producing building envelopes, it is of relevance to mention the development of smart solar devices able to switch their transparency (and solar factor), just as self-powered electrochromic glazing. For example, the Korean company Samsung SDI has been collaborating with KIST (Korean Institute of Science and Technology) for the development of "photovoltaic smart windows" able to use part of the photo-generated current to change their transparency and thus regulate the energy flux transmitted, with obvious savings in terms of energy consumptions of the building where they will be installed (Kalyanasundaram, 2009).

2.6.3. Experimentations with Colour: White Photovoltaics

As already introduced in paragraph 2.6, the maximization of the aesthetic versatility of PV products has become a growing demand in the field of Building Integrated Photovoltaics. Architects are growingly demanding for new solutions to customize the colour of PV elements to make them blend into the building skin.

At the *Centre Suisse d'Electronique et de Microtechnique* (CSEM, www.csem.ch), a breakthrough technology in the field of BIPV has been designed, with early commercialization due by the end of 2015, consisting of white solar PV modules. This technology is characterized by some fundamental elements (from the innermost):

- a solar cell technology that is able to convert efficiently the solar IR light into electricity;
- a selective scattering filter which reflects the whole visible spectrum while transmitting infrared light;
- a light-diffusive layer, which is necessary to give a white appearance to a mirror-like surface.

All these layers combined allow for the attainment of a completely white photovoltaic module with good conversion efficiency levels: the best value, achieved at the CSEM on a 55x60 cm is 11.4%. This value was obtained by relying on high-performing heterojunction crystalline silicon solar cells (HIT), which have a more significant response in the infrared part of the spectrum than conventional crystalline silicon modules and, in general, are characterized by a higher conversion efficiency. Due to the higher cost, however, they did not find the same applicability as conventional crystalline silicon: in actual facts, this latter could be used also for the realization of these white solar modules for BIPV, but the necessity to maximize its IR conversion led to prefer the use of HIT modules.

The necessity to achieve a white appearance obviously leads to a certain loss in efficiency (equal to 40% compared to the same cell technology with "usual" appearance), but — besides the obvious aspects related to the increase of architectural integrability — it leads

Photo 46 - CSEM White PV prototype, presented at 2014 Energy Forum

Photo 47 - Different prototypes of CSEM technology to achieve different colours

Photo 48 - Terracotta-like thin film modules for integration in heritage contexts, developed by Archinsolar (based on CSEM technology) to some advantages as regards the operating performance. First of all, the visible part of the solar spectrum, being reflected, does not contribute to the heating up of the modules: therefore, modules are expected to operate at lower temperatures (Escarré et al., 2014a), compared to standard PV modules, possibly compensating for the lower efficiency. Moreover, Escarré et al. (2014a) underline how this solution, installed on the roof of a building, could have other potential energy-saving relapses by allowing for the mitigation of the so-called "heat island effect" that affects especially big cities. Indeed, which modules could be used to replace the white or reflective paint that in many cities is being used for the finishing of roof surfaces (a practice also refered to as "cool roofing").

Besides the white colour that could actually have a wide application potential for building integration, a great variety of colours is possible with this technology, simply by modifying the "nature" of the film that is placed on top of the solar device (Photo 47, 48 and Figure 2.12). A further advantage of this technology is related to the fact that the cells and related interconnections result hidden and, therefore, modules present a uniform appearance.

As underlined by Escarrè et al. (2014a), the next steps for the development of this technology are to further raise the efficiency of the modules and to integrate them into new applications: indeed, besides building integration, that is the main target of CSEM with this solution, several other sectors might be intersected through this technology (from the car industry to portable devices).

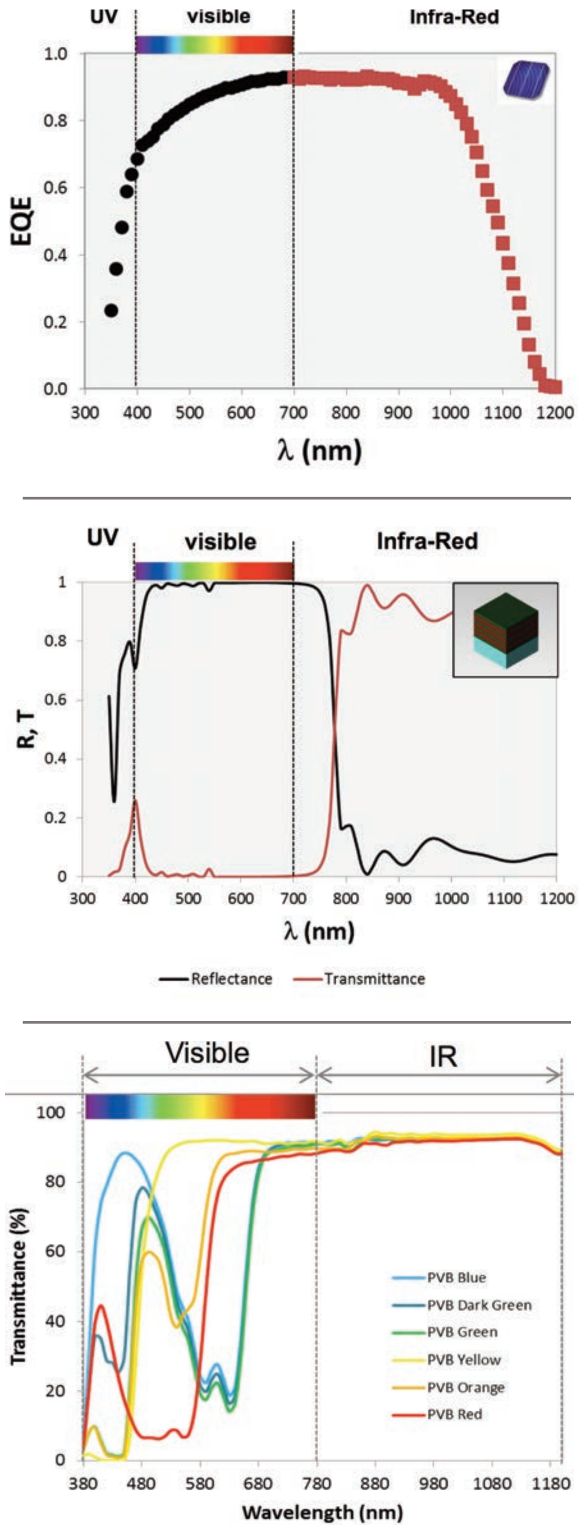


Figure 2.12 - *(top)* Quantum efficiency over the sun's spectrum of the cells used for white PV (Escarrè et al., 2014b); *(middle)* Spectral reflectance and transmittance of the selective reflecting filter (Escarrè et al., 2014b); *(bottom)* Transmittance of the filters used for the attainment of different color appearances (Escarrè et al., 2014b)

2.6.4. Photovoltaics imitating other materials (and possible alternatives)

The acceptance of PV technology is still limited by a series of non-technical factors, often concerning the architectural quality, particularly in listed buildings and in sensitive areas under landscape and monument protection. Photovoltaics indeed introduce in the architectural language new themes and complexities that, if not adequately controlled, can turn out poorly compatible with the characteristics (formal, material, physical etc.) of buildings, especially ancient ones. For example, as underlined in Hermannsdörfer & Rüb (2005), reflective surfaces are often seen as *disturbing* in buildings that are under monument protection. Another aspect can be related to the typical colour of PV cells (mostly in the blue tones) that result quite difficult to integrate with the traditional materials of architecture.

Moreover, in many cases, regulations make most of "traditional" PV installations hardly viable in such protected contexts; at the same time, construction techniques, building materials and architectural traditions vary significantly according to the geographical context. The proliferation of solar roof tiles, already introduced in the course of this chapter, has been one of the effects linked to this issues. A lot of efforts have indeed been addressed to the development of tile shapes and mounting systems able to adapt to the wide variety of cladding elements for pitched roofs, in order to solve the technical issues related to their integration. However, the formal aspects, related to the appearance of these solutions (colours, surface reflectivity, design), have often been underestimated, leading to highly integrated solutions from the constructional point of view, but often criticized as regards the aesthetic results (Kaan, 2009).

In this field, new solutions for the architectural integration have been and are being developed with the specific purpose of modifying the "standard" appearance of PV modules, in order to look like and to imitate other building materials. In this field, one can cite the collaboration, started in 2012, between Italian Dyaqua Art Studio and ENEA[37] that are developing prototypes of PV elements able to accurately reproduce the appearance of traditional building products and materials (i.e. natural stone, roof tiles and wooden boards, as in Figure 2.13 and Photo 49) and specifically thought for the integration of PV into historical contexts.

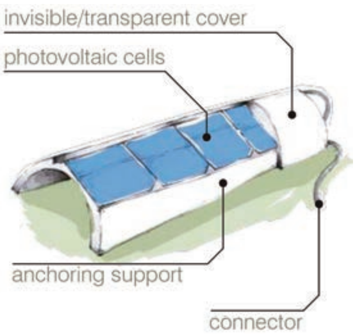


Figure 2.13 - Scheme of the structure of *Coppo fotovoltaico* by Dyaqua Art Studio, (www.dyaqua.it);
Photo 49 - Pictures of "invisible PV" prototypes from Dyaqua's collection

The functioning of this technology is based on the application, on the external surface of the products, of an «*apparently opaque*» element, able to hide the PV cells and, at the same time, to resemble any material. This surface is actually semi-transparent, letting some of the solar energy get through and thus guaranteeing some efficiency. It is evident that, according to the developers of this technology, the lower efficiency deriving from the application of this external covering element will be compensated by the wider integrability scenarios related to the use of this technology, both from the regulatory and architectural points of view (especially in historical centres).

The same principles underlie the "wooden PV modules" presented at 2014 Energy Forum in Bressanone by the Belgian BIPV company, ISSOL (Photos 50, 51). These modules are obtained by printing — on the front glass of more or less standardized PV modules — ceramic, organic or silicon coatings able to reproduce any material texture, while letting part of the solar energy through, with an obvious drop in the efficiency (amounting to 26%, as declared in Quittre, 2014).

Besides the possible debates regarding the *validity* and *authenticity* of such propositions, the intention, in the second case, is even more radical: it is to make photovoltaic modules hardly distinguishable from building materials and, de facto, to make them invisible, even when there are no restrictions regarding e.g. preservation issues. In this sense, one question that arises is whether architects are really interested in such *camouflage* operations or rather in the exploitation of the full potential of photovoltaic technology and of its manifestly "green" and "smart" nature, for the attainment of integration solutions *compatible* with the existing rather than merely *imitative*. In this field, it is worth to cite again the experimentations on colours performed by Archinsolar (linked to the work of CSEM, Photo 48) for the attainment of terracotta-like thin film modules for integration in heritage contexts. It is also worth to mention the research, conducted in the field of the project "PV Accept"[38], leading to the study, development and test in different pilot sites, between Italy and Germany, of novel products for integration of solar energy in highly sensitive areas and buildings under landscape and monument protection.

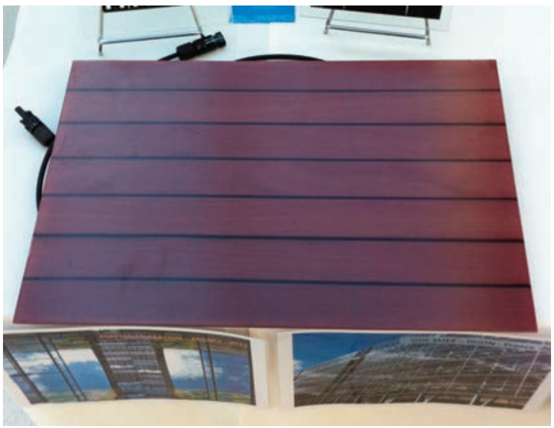


Photo 50 - Prototype of wooden-like PV modules by ISSOL, exhibited at 2014 Energy Forum

Photo 51 - Single-family house cladded with tailor-made wooden-like PV modules by ISSOL

Photo 52 - PV Accept outcomes: *(left)* informative PV installation, S. Giorgio Castle, La Spezia; *(middle)* informative PV installation, Historical Centre, Marbach am Neckar; *(right)* semitransparent product adapted for natural stone and brick

Particular surface structures and treatments for the front glass (e.g. printing of textures and texts for decorative, information or advertising purposes) as well as colour design aimed to adapt to different materials (e.g. natural stone, brick) were tested (Photo 52). Different SMEs in the field of first- and second-generation PV manufacturing were involved, from Würth Solar to Sunways. These experimental installations and solutions resulted from the collaboration of PV manufacturers, research centres and universities from the Arts to the Chemistry field and bear witness a more "architectural" and (in a positive way) complex approach towards the integration of PV technology in the heritage building stock, than those based on making solar modules hardly distinguishable from building products and/or materials.

A peculiar, "extreme" case of imitation of other "materials" by the PV technology is represented by the "Solar Ivy" (http://solarivy.com), a modular and customizable system for renewable energy generation that draws inspiration from ivy growing on a building (Figure 2.14). This system has been developed, since 2011, by the American company SMIT (Sustainably Minded Interactive Technology) and consists of a series of small "photovoltaic leaves" fixed on a stainless steel mesh to be anchored to the façades of buildings for the realization of vertical energy-generating surfaces. In addition, the integration with a piezoelectric element allows also exploiting the energy from the wind. An interesting aspect of this solution for the integration of PV in buildings is related to its great customizability.

Figure 2.14 - "Solar Ivy" by SMIT: *(left)* close rendered view of the solution, in two colors; *(middle)* possible application as finishing/sunshading (www.solarivy.com); *(right)* possible application as finishing/sunshading (Hammer, 2014)

First of all, the light-weight PV devices can either be OPV, a-Si and CIGS, according to the required cost, carbon footprint and electrical productivity; the modules are typically square in shape, but the leaf shape can vary according to different profile options for the supporting element, which can be available in potentially limitless colour options. A lightweight and flexible stainless steel mesh, that is also the element where the electrical connection elements are integrated, can be placed in front of opaque or either transparent surfaces. alongside it, the PV leaves can be disposed according to different desities depending on goals for energy gain, visibility requirements, architectural needs as well as be grouped in order to create various drawings. In Hammer (2014), a discussion of the feasibility and of possible applications of this nature-inspired PV devices is provided, along with some hypotheses for their application in buildings.

2.6.5. Photovoltaics for indoor applications

The will to extend the applicability of photovoltaics in buildings and to find new surfaces for its utilization is also leading to the development of solar devices optimized for indoor energy harvesting. In particular, third-generation technologies are offering potentially cost-effective and lightweight design solutions with very good low-light performance as well as the possibility to be designed for making the most of indoor artificial lighting (as underlined previously in this chapter). As a result, PV elements for the integration into spatial dividers within the envelope, interior doors and windows as well as furniture items and portable objects have begun to be studied and engineered[39]. For example, the VTT Technical Research Centre of Finland has developed a mass production method, based on printing technologies, that allow for the manufacturing of decorative OPV panels (Photo 52), easy to be integrated as wallpaper of internal dividers or into furniture elements and to harvest effectively indoor light[40].

The American architect and MIT lecturer, Sheila Kennedy, together with the materials research group at Kennedy and Violich Architecture (KVA Matx), has studied and developed solar textiles that can be draped like curtains (Photo 53). These membrane-like elements, integrating third-generation OPV devices, can be used in both indoor and outdoor environments to create movable, flexible and energy-harvesting surfaces.

Photo 53 - Decorative, flexible OPV plastic foils for indoor application

Photo 54 - Example of solar textile developed by KVA Matx

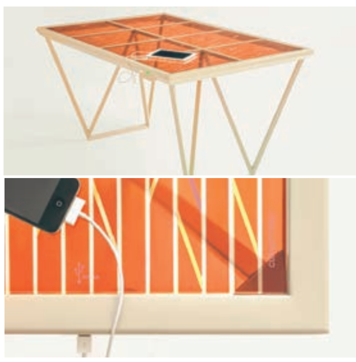


Photo 55 - Current Table developed by Marjan van Aubel and Solaronix

The Dutch designer Marjan van Aubel has integrated DSC glass into doors, tables (Photo 55) and even everyday use objects (such as glasses, plates, forming the so-called "Energy Collection"), enabling them to convert into electricity ambient light to power small devices.

Overall, although the power collected by indoor devices is remarkably lower than that of solar panels for outdoors, these solutions are aimed to maximize the available surfaces for the integration of PV bringing solar energy where conventional technologies can not be used and exploiting the unique material advantages of solar nano-technologies[41]. In this sense, the reduction of the costs becomes a fundamental challenge for these PV devices to be easily integrated into indoor architectural surfaces and design objects.

Notes

1) As already underlined in Chapter 1 (paragraph 1.1), a centralized energy distribution model is characterized by a large-scale power plant serving a large territory and often requiring energy to be transmitted over long distances with deriving distribution losses. By contrast, distributed energy systems are decentralized, characterized by smaller power capacities and typically use renewable energy sources.

2) The aesthetic effect of the PV integration is addressed more in detail in Chapter 3.

3) Cf. www.onyxsolar.com;

4) Cf. www.pv-tech.org/news/zsw_leading_eu_funded_cigs_thin_film_sharc25_project_to_25_conversion_effic

5) Modules (PowerFLEX BIPV 300W) manufactured by Global Solar (www.globalsolar.com); see also "*Top 10 World's Most Efficient CI(G)S Modules*", Retrieved from www.solarplaza.com/top10-cigs-module-efficiency/.

6) This number is calculated by multiplying efficiency (13%) by 1000 to get output watts per square meter (130 W/m2), and then multiplying power by the stated cost of $0.8-1.0 per watt to get something more than $100-130/m^2 (91-116 €/m^2). Cf. Noufi (2013); *CIGS lead module price fall*, January 2013, http://www.pv-science.org.

7) CleanTechnica. (2013). *First Solar Reports Largest Quarterly Decline In CdTe Module Cost Per-Watt Since 2007*, Retrieved from: http://cleantechnica.com/2013/11/07/first-solar-reports-largest-quarterly-decline-cdte-module-cost-per-watt-since-2007/

8) Cf. www.solarchoice.net.au/blog/news-speed-of-bipv-growth-depend-technological-advances-types-materials-300414

9) *Heliatek announces world record for organic cell*, January 2013; cf. http://www.pv-magazine.com/news/details/beitrag/heliatek-announces-world-record-for-organic-cell_100009859/#axzz2wrhiJVFm

10) *Heliatek breaks efficiency record for 40% transparent organic cells*, March 2014; cf. www.pv-magazine.com/news/details/beitrag/heliatek-breaks-efficiency-record-for-40-transparent-organic-cells_100014600/#ixzz3cJ2cZR29;

11) Heliatek GmbH, www.heliatek.com;

12) Production is based on vacuum coating of organic semiconductors, which is an already consolidated technology for the mass-production of OLED displays. The low-temperature coating process in the vacuum line allows a roll-to-roll manufacturing of OPV modules on plastic substrates like PET. Cf. Erk, 2012.

13) Belectric acquired the assets of the American OPV company Konarka Technologies, which filed for bankruptcy in 2012. Cf. www.belectric.com/en/organic-photovoltaics; www.solarte.de;

14) *HeliaFilm® on concrete façade: tomorrow's clean and green power supply.* Press Release, May 2015. Retreived from: http://www.heliatek.com/newscenter/latest_news/heliafilm-an-der-betonfassade-saubere-und-gruene-stromversorgung-von-morgen/?lang=en#

15) *Heliatek enters Chinese market with the world's first BIOPV concrete façade installation.* Press Release, December 2014. Retreived from: http://www.heliatek.com/newscenter/latest_news/heliatek-erobert-den-chinesischen-markt-mit-einer-ersten-biopv-betonfassaden-installation/?lang=en#
16) The British company G24i has been the first to set up a production line in 2010 for flexible DSC and addressed the consumer electronics market, providing flexible solutions for portable applications mainly (cf. www.gcell.com).
17) «...*Fujikura enhanced this characteristic of DSSCs utilizing our material technology and achieved a substantial 18% conversion efficiency under a 500 lux environment with fluorescent or LED lights...*». Cf. Fujikura. (2012). *Fujikura dye-sensitized solar cells now offer 18% energy conversion efficiency*, *Press Release.* Retrieved from http://www.fujikura.co.jp/eng/f-news/2035577_4207.html.
18) The narrow-rectangular shape of the cells is due to the necessity to reduce internal resistances that might otherwise compromise the efficiency of the devices.
19) Dyesol (www.dyesol.com), born in 2008, is a supplier and manufacturer of materials, equipment and know-how regarding DSC as well as solid-state technology, based on Perovskite. It has expanded internationally to strategic locations around the World such as the UK and Switzerland and teamed up with different building companies in different countries in order to bring DSC-based BIPV products into the market.
20) Cf. http://www.marjanvanaubel.com
21) Re-elaborated from Muller, 2014.
22) «...*The solar panels of tomorrow will be transparent, lightweight, flexible, and ultra-efficient. We'll be able to coat shingles or skylights or windows with them — and it'll all be as cheap as putting up wallpaper...*». Plumer, 2015.
23) It is important to make a distinction between flat and pitched roofs, since the corresponding technical solutions (especially as regards the weatherproofing layer) are significantly different.
24) www.coversun.it; www.cappellogroup.it.
25) As highlighted by Weller et al. (2010), the BIPV industry suggests at least 20-mm thick cavity on the back of the modules and a ventilation cross section of 200 cm^2/m, as also stated in DIN 4108-3.
26) Cf. *AWM Carport Munich featuring the combination of ETFE roofing and photovoltaic modules,* July 2012, http://www.makmax.com/news/2012/nw0705.html;
27) DIN 18516:Part 1:2010. (2010). *Cladding for external walls, ventilated at rear - Part 1: Requirements, principles of testing.* Deutsches Institut für Normung DIN.
28) Available at http://leso2.epfl.ch/solar/index.php;
29) Available at http://www.bipv.ch/index.php/en/products-en-top;
30) Cf. http://www.3tu.nl/bouw/en/PDEng/Luminescent%20Solar%20Concentrator;
31) Cf. http://siser.eps.hw.ac.uk/research/concentrating-pv/luminescent-solar-concentrators-lscs;
32) Based on measurements of samples with dimensions that do not exceed 100x100mm^2 and with no significant visible-range transparency. De facto, ensuring high transparency in high-efficiency concentrators remains problematic because of IR-luminophore limited availability. Cf. Alghamedi et al. 2014.
33) Cf. http://www.3tu.nl/bouw/en/PDEng/Luminescent%20Solar%20Concentrator;
34) By making a simple division, this corresponds to 8.3 Wp/m^2 of installation area, which is a very low value. However, it must be highlighted that the installation area does not coincide with the active area (indeed, the solar cells are placed on the edges of the 192 sheets and not on their sun-exposed surfaces); Cf. www.eni.com/it_IT/attachments/azienda/eni-cultura/iniziative-speciali/maker-faire-rome-2014/pdf/progetto-lsc.pdf.

35) For example, 40% transparency in the PV layer means that 40% of this “most energetic” part of the solar spectrum is let through the PV element and only the remaining 60% — without considering the possibly reflected part — can be used for the PV conversion.

36) «*...Concentrators of this type can be called ‘‘hybrid’’, since luminescence effects play only a partial role in energy harvesting functionality, together with multiple scattering and diffraction enabled by embedding quasi-random disordered arrays of luminophore particles inside polymer interlayers...*», Alghamedi et al. 2014 (p. 2).

37) The first is an R&D lab, founded in 2000 and specialized in the realization of solutions for the aesthetic and architectural integration of new technologies, with a great focus on design and arts (www.dyaqua.it); the ENEA is the Italian National Agency for New Technologies, Energy and Sustainable Economic Development.

38) PVACCEPT was a German-Italian research and demonstration project (2001-2004), funded by the European Commission within the programme "Innovation and Small and Medium Sized Enterprises" and aimed at developing marketable PV modules, whose innovative design would enable new possibilities of integration into old buildings, historical sites, urban spaces and landscapes (Cf. www.pvaccept.de/pvaccept/eng/index.htm).

39) An interesting scenario, in this field, is related to the so-called Internet of Things (IoT).

40) Cf. http://www.vttresearch.com/media/news/decorative-and-flexible-solar-panels-become-part-of-interior-design-and-the-appearance-of-objects.

41) «*...Le nanotecnologie offrono la possibilità del tutto nuova di spingere il design del dettaglio strutturale su una scala del tutto diversa rispetto alla consuetudine progettuale, permettendo a seguito di una idonea calibrazione di spessori e proprietà dei materiali su scala nanometrica, di progettare a fundamentis i livelli prestazionali dell’involucro edilizio...*». Cannavale, A. (2011). Nanomateriali e nanodispositivi per l’involucro edilizio trasparente. In Trento, A. (Ed.). *L’attività di ricerca nel dottorato, Verso un sapere tecnico condiviso, Atti della giornata di studio*, Università di Roma “La Sapienza”, 18 Febbraio 2011, Roma: Associazione Scientifica Ar. Tec., 2011.

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Photo References

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Photo 3 - Daily Overview (www.dailyoverview.com)
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Photo 36 - www.ackermann-ingenieure.de
Photo 37 - www.etfe-mfm.com
Photo 38 - Maximilian Dörrbecker
Photo 39 - Sunways
Photo 40 - ©Romag (www.romag.co.uk)
Photo 41 - ©J-L Laloux
Photo 42 - Øyvind Aschehoug, NTNU
Photo 43 - Donna Coveney
Photo 44 - MIT Technology Review
Photo 45 - Yimu Zhao (www.sunwindenergy.com)
Photo 46 - Photo of the Author
Photo 47 - ©CSEM (http://www.gizmag.com/csem-white-solar-panels/34463)
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Photo 51 - Quittre, 2014
Photo 52 - www.pvaccept.de/pvaccept/eng/pressinfo.htm
Photo 53 - Antti Veijola
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CHAPTER 3
Architecture, Photovoltaics and Case Studies
Architettura, Fotovoltaico e Casi Studio

ABSTRACT_ITA - *Il panorama architettonico degli ultimi due decenni offre numerosi esempi di edifici di nuova costruzione e di interventi di riqualificazione dell'esistente, in cui il fotovoltaico diventa parte integrante del processo progettuale, non solo per gli aspetti concernenti la produzione di energia ma anche, più in generale, per quelli propriamente legati alla funzionalità, all'efficienza energetica e all'estetica dell'edficio. Ciononostante, numerosi studi hanno dimostrato come esistano ancora alcune barriere che limitano l'impiego del fotovoltaico negli edifici e come spesso queste riguardino aspetti legati al-l'accettazione delle soluzioni utilizzate, specialmente sul piano della qualità architettonica.*

Il presente capitolo analizza e commenta alcuni dei lavori che in letteratura hanno tentato di identificare dei criteri per una corretta integrazione architettonica del fotovoltaico. A partire da questa analisi e da un approfondito studio di esempi emblematici di integrazione architettonica del fotovoltaico, si sono individuati una serie di criteri ritenuti significativi ai fini della valutazione del "livello di integrazione" del fotovoltaico in un edificio. Tali criteri sono discussi nel dettaglio con il supporto di numerosi esempi realizzati e, in particolare, riguardano: la strategia di progetto che ha guidato alla definizione delle caratteristiche dell'integrazione; la multifunzionalità dell'installazione, non solo per quanto riguarda il ruolo tecnico-costruttivo del fotovoltaico all'interno del sistema tecnologico dell'edificio, ma anche nella definizione dell'immagine dello stesso; le caratteristiche bioclimatiche, che si riferiscono alle possibili ricadute in termini di risparmio energetico derivanti dall'integrazione del fotovoltaico, indipendentemente da quelle strettamente legate alla produzione di energia; gli elementi di innovazione che si possono individuare nelle caratteristiche del modulo, dell'installazione, ma anche a livello del concept generale dell'edificio.

Alla fine del capitolo, numerosi esempi realizzati di integrazione architettonica del fotovoltaico sono presentati sotto forma di schede di caso studio, nelle quali la maggior parte delle informazioni relative all'edificio analizzato nonché alle caratteristiche dei prodotti impiegati e dell'installazione fotovoltaica, sono sintetizzate e riportate nel dettaglio. In ciascuna scheda, i criteri proposti sono applicati allo scopo di permettere una valutazione del livello di integrazione del fotovoltaico.

ABSTRACT_ENG - *The architectural panorama of the last two decades offers several examples of either new or retrofitted buildings, where PV is considered since the early design stages as an integral part not only of the design process, but also of technical elements of the architectural cladding thanks to BIPV market developments. However, several studies demonstrated how still some barriers exist in the acceptance of PV use in buildings and how these barriers are often related to the concerns about the architectural quality of the chosen solutions.*

This chapter analyzes and discusses some of the works that in literature have attempted to identify some criteria for a correct architectural integration of photovoltaics in buildings. Starting from this discussion and from an in-depth analysis of successful case-studies of architecturally integrated photovoltaics, a list of features that are considered relevant to define the integration level of an example of PV use in buildings have been defined and four criteria for the assessment of the PV integration have been elaborated.

These criteria are widely discussed with the support of plenty of examples and, in particular, regard: the design strategy that has led the project of each installation; the multi-functionality of the PV installation, taking into account the added technical-constructional functions of the PV system in the building fabric as well as the potential role PV plays for the definition of building appearance; the other bioclimatic features, focusing on the potential energy-saving relapses related to the use of the PV system, besides those related to its electricity production; the elements of innovation, referring to the novelty of module design, module installation and/or of the integration concept.

At the end of the chapter, a consistent number of built examples of architectural integration of PV is presented by means of case-study sheets, where all main information are reported synthetically and detailedly. In each of the case-study sheets, the proposed criteria are applied too in order to allow for a synthetic evaluation of the example of PV use in the analyzed building and of its integration level.

3.1. Introduction

The possibility to integrate active solar energy technologies (i.e. photovoltaic and solar thermal systems) into buildings has been and is acknowledged as a very significant opportunity to transform buildings from energy consumers to energy generators. At the same time, since the beginning, it has represented a big challenge for architects, engineers, and all actors involved, due to the complexity of different levels of planning involved.

As widely discussed in the previous chapter, the advances achieved in the field of PV technologies, on the one hand, allowed for a decrease in the cost of solar modules and, on the other hand, for the birth of new products with new features, particularly fit for architectural purposes: lightness, semi-transparency, flexibility, variety of color, grain and texture, etc. These factors gave momentum to the spread of PV technology into the building stock and, in particular, to the BIPV sector, which, although a niche of the photovoltaic market, has been significantly growing lately.

However, reduced prices as well as improved technical performance and choice of products are not sufficient for increasing acceptance and wider use of these systems. Nowadays, there is still a significant discrepancy between the perceived importance of the use of solar energy systems in architecture and their actual use in buildings, as emerged from an international survey involving over 600 architects in 2012 (Farkas & Horvat, 2012)[1]. Only a fraction of the available roof and facade surface for architectural integration of active solar energy systems are effectively used for solar thermal power and PV.

Still some barriers remain in the perception of the use of PV in buildings not only as regards the full understanding of its advantages, but also in terms of acceptance. De facto, different studies in literature have evidenced the persistence of some slightly negative perceptions of active solar energy technologies in buildings, underlining: how still some architects consider BIPV not attractive/aesthetic (Montoro et. al, 2010; Kaan, 2009); how some architects fear that decisions related to solar design at the building stage can significantly constrain the range of forms available to the designer, demonstrating, at the same time, that it is actually the opposite (Otis, 2012); how very often "solar" buildings are criticized for their lack of architectural quality (Krippner, 2003).

These negative perceptions are fundamentally linked to the multitude of examples of random component placement on the roof (Krippner, 2006)[2], which is a significantly more widespread practice probably because it is believed to be less demanding, both in terms of components and implementation costs, compared to more "integrated" approaches. This is often due, as the above-introduced survey has also pointed out, to lack of specific technical knowledge regarding the use of PV devices as architecturally relevant components and the related benefits. As also underlined by Krippner, 2003 speaking of the architectural integration of PV, «*…many architects still refuse to address the topic and leave the issue in the hands of engineers and builders; on the other hand, it seems even more difficult to define what constitutes quality given the complexity of the requirements and the abundance of system choices…*» (p. 27).

At the same time, the above-introduced negative perceptions seem to underestimate the increasing number of successful built examples of architecturally integrated photovoltaics. Indeed, the architectural panorama of the last two decades offers several examples of either new or retrofitted buildings, where PV is considered since the early design stages as an integral part not only of the design process, but also of technical elements of the building envelope thanks to (BI)PV market developments. Some of the biggest names in the contemporary architectural world (e.g. Norman Foster, Mario Cucinella, Frank O. Gehry, Renzo Piano, Toyo Ito) have also experimented in this field, offering outstanding and internationally acknowledged examples of a multidisciplinary and systemic approach to the integration of solar energy in architecture (see Photos 1, 2).

In this framework, it is not coincidence that several studies have attempted to define some criteria for a correct architectural integration of photovoltaics in buildings, driven by the necessity to improve the awareness of the stakeholders involved in the process (architects, engineers, energy consultants, PV manufacturers, governments and policy-makers, customers, etc.) and to incentivize a more conscious use of PV in architectural projects, not only in relation to new constructions, but also to the energy retrofit of existing buildings. This chapter will describe and discuss the studies that tried to give some tools, parameters and/or criteria for the evaluation of the architectural and technological quality level of a PV integration in buildings. Starting from this discussion and from an in-depth analysis of built examples of architecturally integrated photovoltaics, some criteria for the evaluation of the integration of the PV technology into buildings are proposed as well.

Photo 1 - SIEEB, Mario Cucinella Architects, 2006: View from the inner court of the PV panels installed as sunshading elements of building south-facing terraces

Photo 2 - Masdar Institute of Science and Technology, Foster + Partners, Abu Dhabi, 2012: View of one of the inner courts and of the PV system on the roof

At the end of the chapter, a large number of built examples of architectural integration of PV is presented in the form of case study sheets, where all main information regarding the selected example are reported synthetically and detailedly. In each of the examples, the proposed criteria are applied too in order to allow for a synthetic evaluation of the example of PV use in the analyzed building and of its integration level.

Overall, the objectives of this chapter are to give a contribution to a wider knowledge on the theme of the architectural integration of photovoltaic and to offer an insight into the use and arrangements of photovoltaics in architecture, containing detailed information at both project and product levels and focusing on architecturally relevant data[3]. In parallel, the work aims to provide some criteria for the evaluation of the architectural integration level and to individuate some key-features for the success of the examples analyzed, in order to incentivize a more conscious use of photovoltaics in architecture.

3.2. Assessing the Quality of an Architectural Integration of PV

The architectural integration is a lot more than installing solar panels on the surfaces of a building, it is a complex process that involves different professional competences and requires a balance of often conflicting aspects referring to aesthetic, technical-constructional and energy-related issues (Weller et al., 2010). For an integration to be successful, indeed, it is not sufficient that the solar components fulfill functional and/or constructive aspects, but it is fundamental to consider a multiplicity of design aspects (Krippner & Herzog, 2003) that often lie on more subjective and interpretative levels and may vary significantly depending on the characteristics of each project.

Based on this consideration, several authors have underlined how at least two different levels of integration of active solar technologies, in general, can be individuated and these are the following:

- a *constructional integration*, which refers to the technical-functional role of the solar modules into the building system;
- an *aesthetic integration*, which refers to the building design concept.

According to the technical-functional role that the PV product plays into the building system, we can distinguish two types of systems, which have been already widely discussed in the previous chapter: Building Added and Building-Integrated. In the first case, the solar modules are mounted on top of the already finished building skin and are most commonly considered just as technical

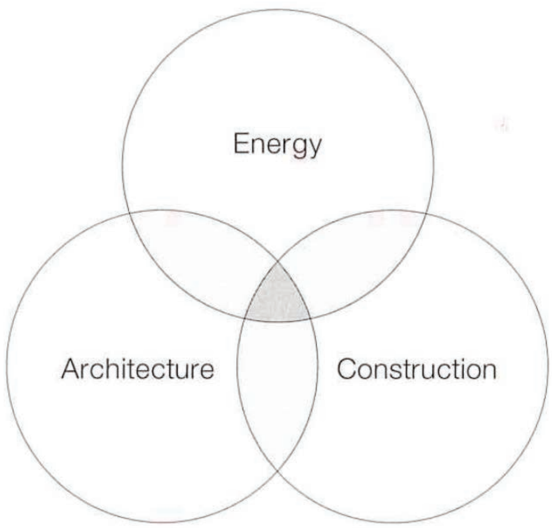


Figure 3.1 - The building design as a symbyosis of architecture-, construction- and energy-related requirements (Weller, 2010)

devices added to the building, with their own supporting structure. The only technical function they are called to fulfill is the electricity production. With Building-Integrated Photo-Voltaics (BIPV) is instead meant a multifunctional building and PV element able to substitute one or more building technical elements and/or functional layers.

In both cases, in order to establish whether we are in front of a good quality system, technical-functional aspects can be in some ways evaluated more or less directly by referring to predicted and/or measured performance as well as to a series more objective and quantitative parameters, defined in technical standards and regulations.

Discussing about the quality of a PV integration, Reijenga (2003), for example, distinguished among: a *technical quality* of the BIPV system, regarding PV aspects such as cables and inverters; a *building quality* of the BIPV system[4], taking into account its multifunctional performance as a building element; and an *aesthetic quality*. The first two aspects regard the correct functioning of the system and are therefore considered as preconditions by the author, whereas the aesthetic quality — that is acknowledged as the most subjective part in the assessment of BIPV quality as well as the most important for its acceptance — is analyzed separately through the definition of specific criteria, presented and discussed in par. 3.2.1.

The aesthetic integration, indeed, is more difficult to be defined in a unique way. The aesthetic quality of the integration has to be understood as the PV capability to define the linguistic/morphological rules governing the structure and the composition of the building. However, any aesthetic definition cannot determine with certainty and objectivity what is beautiful in terms of integration, but a critical study of built examples and of existing references can be useful to define some best practices[5].

Regardless of whether the system is mounted on top of the already finished building envelope or integrated into it (this, indeed, only refers to the *constructional level* of the integration), to establish if we are in front of an architectural integration is not immediate: it is necessary to define which parameters have to be taken into account. The following pages are focused on the analysis and discussion of the works that in literature have attempted to identify these parameters and have provided some criteria for a correct architectural integration of photovoltaics (and, more in general, active solar technologies) in buildings or either for the evaluation of its architectural quality.

3.2.1. IEA-PVPS Task 7: PV in the Built Environment

The International Energy Agency - Photovoltaic Power Systems Programme (IEA-PVPS) is a collaborative R&D agreement[6] established within the IEA. Since its establishment in 1993, the participants have been conducting a variety of joint projects related to the application of photovoltaic technology. Such projects are organized in Tasks, some of which have already been completed, and within each task several national and international publications, conferences, workshops, market assessments and studies are carried out with the aim to collect and spread knowledge and information about present status, trends, and various aspects of the photovoltaic industry.

The IEA-PVPS Task 7: PV in the built environment started in 1997 and its declared objective was «*…to enhance the architectural quality, the technical quality and the economic viability of PV systems in the built environment and to assess and remove non-technical barriers for their introduction as an energy-significant option…*». In the field of this project, some architectural criteria for evaluating the quality of the PV technology in buildings have been defined and they are reported in the Table below (Schoen et al., 2001).

1. NATURALLY INTEGRATED
The PV system is a natural part of the building. Without PV, the building would be lacking something - the PV system completes the building.
2. ARCHITECTURALLY PLEASING
Based on a good design, does the PV system add eye-catching features to the design
3. GOOD COMPOSITION
The colour and texture of the PV system should be in harmony with the other materials. Often, also a specific design of the PV system can be aimed at (e.g. frameless vs. framed modules)
4. GRID, HARMONY AND COMPOSITION
The sizing of the PV system matches the sizing and grid of the building
5. CONTEXTUALITY
The total image of a building should be in harmony with the PV system. On a historic building, tiles or slates will probably fit better than large glass modules
6. WELL-ENGINEERED
This does not concern the watertightness of PV roof, but more the elegance of design details. Have details been well-conceived? Has the amount of materials been minimized? Are details convincing?
7. INNOVATIVE NEW DESIGN
PV is an innovative technology, asking for innovative, creative thinking of architects. New ideas can enhance the PV market and add value to buildings.

Table 3.1 - Integration Criteria according to IEA-PVPS: Task 7 (Schoen et al., 2001)

These seven criteria, elaborated more than ten years ago, have been and still are an interesting reference that embraces the majority of aspects regarding the relationship between PV and Architecture (the role of PV into the overall perception of the building; solar module capacity to add visual appeal to a building; the harmony among PV modules and other building materials in terms of colors and textures as well as of grids and dimensions; the elegance of technical details). The criteria, however, are based on qualitative considerations and do not seem to be fully objective for the comparison of one building to the other. As also underlined in more recent works (Munari Probst 2008), the use of words such as *natural, good, pleasant* do not seem to define the characteristics of the integration leading to the architectural quality. It could be noted how, even if this is not directly stated, the “visibility” or “recognizability” of the PV system is considered as a relevant aspect in the definition of the architectural quality: this could be deducted, for example, from the second criterion, where PV system is required to add *eye-catching* features to the design in order to be acknowledged as *architecturally pleasing*; it could also be deducted from the first criterion where, for a good-quality *natural* integration, the PV system should be completing the building in a way that the building itself would result lacking something without it. Actually, this might exclude from the examples of good-quality integrations according to IEA-PVPS Task 7 workgroup, several buildings where a more discreet appearance of the photovoltaic system is pursued or either imposed for reasons related to e.g. compatibility with the existing, especially in renovation projects dealing with historic architectural contexts.

As for the other criteria, the last one deserves specific attention for the relevance given to the innovation in the design of the PV integration into buildings, as an aspect able to «*enhance the PV market and add value to buildings*». Innovation in design here is only attributed to creative thinking of architects, but it actually should come from a close collaboration among all stakeholders into the building and PV industries and it could involve, as it will be widely discussed later in this chapter, the design of the single components and their installation as well.

In these criteria, the architectural quality of either building-integrated or building-added PV systems is analyzed only by taking into account the aspects regarding its aesthetic result, without accounting for the functional and constructional, which are considered as preconditions (Reijenga, 2003). This might lead to underestimate the potential as well as the complexity of the architectural integration process. For example, the multi-functionality is not either awarded or underlined as a distinctive element for the level of an architectural integration, among these criteria. This is instead a fundamental issue to consider, especially in terms of cost.

3.2.2. IEA-SHC Task 41: Solar Energy and Architecture

The Task 41 of the International Energy Agency - Solar Heating and Cooling (IEA-SHC) Programme[7], entitled "Solar Energy and Architecture" is a quite recent and very important contribution in the research on both PV and solar thermal systems in buildings. The vision behind this project was «*...to make architectural design a driving force for the use of solar energy...*»[8]. The project is addressed specifically to architects in order to provide them with tools and useful guidelines for the correct integration of PV into buildings.

Architectural integration quality — referred to both solar thermal and photovoltaic systems — is defined here as «*...a result of a controlled and coherent integration of the solar collectors simultaneously from all points of view, functional, constructive, and formal (aesthetic). When the solar system is integrated in the building envelope […] it must properly take over the functions and associated constraints of the envelope elements it is replacing (constructive/functional quality), while preserving the global design quality of the building (formal quality). If the design quality is not preserved (i.e. the system is only constructively/functionally integrated into the building skin without a formal control), we can only call it a building integrated system...*» (Munari Probst & Roecker, 2012, p. 7).

This definition, which is actually quite in line with that provided earlier in this work at paragraph 2.1, is interesting because it clearly underlines how integrating functionally and constructionally solar systems into the building envelope (by using multifunctional products) is a relevant advantage; however, it is not sufficient to achieve the architectural integration quality, which is also depending on the aesthetic control of the integration.

As for the functional-constructional aspects, the work refers to the respondency of the solar modules and/or BIPV products to the building and PV construction standards.

As for the formal aspects, the following characteristics are underlined as criteria for a good integration of active solar technologies in Munari Probst & Roecker (2012, p. 8):

- *«...the position and dimension of collector field(s) have to be coherent with the architectural composition of the whole building (not just within the related façade);*
- *collector visible material(s) surface texture(s) and colour(s) should be compatible with the other building skin materials, colours and textures they are interacting with;*
- *module size and shape have to be compatible with the building composition grid and with the various dimensions of the other façade elements;*
- *Jointing types must be carefully considered while choosing the product, as different jointing types underline differently the modular grid of the system in relation to the building...».*

The above-mentioned integration criteria are reprised from a previous work by the same author (Munari Probst, 2008), mainly focused on solar thermal technologies and where they are also widely described and correlated with an analysis of built examples[9]. Among the criteria, the recurring words are coherent and compatible meaning that the PV system can not be evaluated without also taking into account the building that is it installed onto. In other words, successful integration needs to be coherent with the global building design logic (Munari Probst, & Roecker, 2007). As a result, a very wide interpretability can be attributed to the above characteristics[10].

Within the work of Task 41, some case-study buildings are presented as good integration examples of either mono-functional added PV systems or multi-functional integrated ones and subjected to an integration quality evaluation, according to some "integration achievements". These are simply evaluated for each of the presented case-study buildings with +, - or +/-, based on the above-introduced integration criteria and are listed as follows:

- *Module used as multifunctional construction element;*
- *Field position and dimension;*
- *Visible materials;*
- *Surface texture/pattern;*
- *Module color;*
- *Module shape & size;*
- *Jointing/Fixing.*

Looking at the integration achievements proposed in the Task 41, it is possible to note how all parameters, except for the first one (i.e. module used as multifunctional construction element), refer to aesthetic features of the PV system, meaning that only the formal aspects of the integration quality are evaluated through the use of these achievements.

The multi-functionality of BIPV systems is also considered as an achievement to evaluate the quality of the architectural integration quality of the case-studies[11]. The use of PV modules as multifunctional construction elements is recognized as an added-value bringing major advantages on the global cost reduction and an enhanced architectural quality but, at the same time, requiring an extra effort to building designers.

3.2.3. BiPV.tool: a method for the evaluation of PV in buildings

An interesting approach for the assessment of the integration quality of PV in buildings has been carried out by a group of research between Italy and Switzerland in its scientific activity[12]. Starting from the consideration of the insufficient spread of PV integration concepts in real constructions, they have tried to define some "quality control" tools, similarly to the experience of energy and environmental certification. In particular, a multicriteria and multiscale scoring method, called *Bipv.tool*, was defined in order to assess several *qualitative, quantitative and multi-scalar aspects* of BIPV. The method is «*…conceived as a multi-criteria grid of evaluation, based on different classes of integrability, scales of scoring and weighting criteria, that ranges from architectural aspects to constructive and energetic ones. Scores, derived from this series of qualitative and quantitative requirements, leads to a brief final score for the examined project…*» (Bonomo & De Berardinis, 2012, p. 4183).

This semi-qualitative evaluation methodology starts from the recognition of the complexity of BIPV concept, which relates to architecture, building technology, energy efficiency, electricity generation and building systems and pertains also to different scales from urban, to building and its details. As a result, it evaluates PV integration from several points of view, only neglecting — as the authors themselves underlined — the economic aspects of the PV integration. The method is subdivided in three different levels, summarized in Table 3.2, top.

BiPV Tool		
I	7 CLASSES OF INTEGRABILITY	% weight
II	27 CRITERIA	% weight
III	143 REQUIREMENTS	-1 to +5 score

	Class of Integrability	Objective of the Assessment	%
1	Procedural	*Regulatory and legal system that addresses procedural conditions, limits, incentives*	5%
2	Morphological Figurative	*Quality of aesthetic and formal characterization of the architectural language*	30%
3	Technological Constructive	*Constructive role in the technological system*	15%
4	Building Performance	*Level of satisfaction of technological requirements*	15%
5	Bioclimatic Ecological	*Energy-saving and environmental efficiency throughout the building lifecycle*	15%
6	Energetic Plant	*Principles of solar design and electrical efficiency*	15%
7	Landscape Contextual	*Coherence and acceptability with a system of contextual values to be protected*	5%

Table 3.2 - *(top)* summary of the structure of BiPV.tool method; *(bottom)* list of the Classes of integrability individuated in the BiPV.tool as well as the corresponding objectives and weighs (Bonomo & De Berardinis, 2012)

1	**PROCEDURAL**	**5%**
1.1	Possibility to access to incentives	50%
1.2	Possibility to access to bonus tariffs	20%
1.3	Compliance with special rules	30%
2	**MORPHOLOGICAL FIGURATIVE**	**30%**
2.1	Linguistic-morphogenetic PV role	20%
2.2	Recognizability of the PV skin and dialectical relationship with building envelope	15%
2.3	Dimensional-morphological coordination of PV surface	20%
2.4	Linguistic/aesthetic control at component scale	15%
2.5	Innovation in design	15%
2.6	Figurative role of other parts	
	2.6.1. Wiring, connections, cables	*5%*
	2.6.2. Structures and application systems	*5%*
	2.6.3. Inverter, batteries	*5%*
3	**TECHNOLOGICAL CONSTRUCTIVE**	**15%**
3.1	Type of Integration	40%
3.2	Constructive role	30%
3.3	Couple Ability	30%
4	**BUILDING PERFORMANCE**	**15%**
4.1	Degree of satisfaction of building requirements	60%
4.2	Interference on technological quality	25%
4.3	Strategy of technological innovation	15%
5	**BIOCLIMATIC ECOLOGICAL**	**15%**
5.1	PV effectiveness in global energy efficiency	
	5.1.1. Ability to satisfy the electricity demand	*40%*
	5.1.2. Contribution in the global energy demand	*40%*
5.2	PV environmental impact	
	5.2.1. Recycling	*15%*
	5.2.2. Embodied energy in PV plant	*5%*
6	**ENERGETIC PLANT**	**15%**
6.1	Choice of PV material	10%
6.2	Maximising/optimizing the producible energy	20%
6.3	Adequate placement of PV modules	20%
6.4	Limitation of shading on PV modules	10%
6.5	Limitation of dirt on PV modules	10%
6.6	Control of module temperature	20%
6.7	Control of albedo factor	10%
7	**CONTEXTUAL-LANDSCAPE**	**5%**
7.1	Landscape character of context	30%
7.2	Intervention on contextual quality	70%

Table 3.3 - List of the evaluation criteria for each class of integrability (Bonomo & De Berardinis, 2012)

In particular, 7 classes of integrability are individuated, corresponding to different aspects of the photovoltaic installation that can be taken into consideration for its evaluation (Table 3.2, bottom). Each class is given a weight (%), in order to distinguish the most relevant ones from the least significant and individuate some sort of priority among them. The classes of integrability are in turn subdivided into 27 criteria, which are reported in Table 3.3[13]. Finally, each criterion entails different requirements, which can either be qualitative and quantitative and to which a score from -1 to 5 can be assigned in order to obtain a synthetic final score for the project.

Several interesting aspects could be highlighted. First of all, the number of classes shows the multiplicity of different levels that are interested by the photovoltaic integration within the planning process (legal-procedural, aesthetic, constructional, functional, energetic, bioclimatic, urban-contextual).

The morphological-figurative role of PV is given the highest weight among all classes; this bears witness of the importance, given by the authors, to the aesthetic performance of PV for the evaluation of an architectural integration project. A great relevance is also attributed to the constructional role of a PV system in the building fabric, i.e. when it is considered not only as a plant for the production of clean electricity, but also as a technical element and/or functional layer of the building system: therefore, this methodology awards multifunctional BIPV systems in its evaluation of PV use in buildings. Actually, the effective performance of the PV system is evaluated from three different points of view and, in particular, as: energy-producing (class 6: "Energetic Plant"), potentially energy-saving (class 5: "Bioclimatic Ecological"), and building technical (class 4: "Building Performance") solution.

In particular, in the fifth integrability class (Bioclimatic Ecological), the authors refer to the capacity of the system to contribute to global energy demand of the building. This is actually a very important aspect — that is analyzed more in detail later in this chapter at paragraph 3.4.3 — since particular types of integration might have a remarkable, not only active, but also passive, impact on building energy performance. Moreover, among the criteria, the environmental impact of PV, taking into account aspects such as the embodied energy related to the system and its recyclability, is considered as well.

Looking more in detail at the specific class of integrability regarding the morphological and figurative role of PV, it is important to note how the multi-scalarity of the approach where the various criteria regard both the building and the component scale, so one can find a criteria such as: "Linguistic-morphogenetic PV role" (2.1), dealing with the possibility of PV to «*…contribute to the genesis of the shape of the architectural organism…*» (Di Gianni & Bonomo 2011); "Linguistic and aesthetic control at component scale" (2.4), regarding the basic figurative characteristics of cells and modules, from color to surface texture (which are then assessed more directly through scoring, as requirements); "Figurative role of other parts" (2.6), entailing the appearance of the complementary elements of the system (i.e. wiring, cables, inverters, supporting elements, and so on) that, if not adequately controlled, might alter the overall perception of the plant.

It is of relevance to note how, also here, as in the work of Task 7 of IEA-PVPS program, the innovation in design is acknowledged among the criteria defining the quality of the architectural result of the integration[14].

Furthermore, one of the criteria within this integrability class also regards the recognizability of the PV skin, which can either be hardly visible or dominant: however, the recognizability of the solar system is not a value per se, but it should be carefully considered case by case. The weighting method, in this sense, is an interesting solution that can help, for example, distinguishing new construction and retrofit interventions, where different considerations must be done. For example, a highly recognizable integrated PV system might be seek for in a new construction, but in the field of retrofit operation and depending on the context of intervention, a more discreet integration might be a better option. Another interesting example might regard the integrability class regarding constructional role of the PV system: this class could be given a higher weight in new construction examples than in the field of refurbishment interventions, where in some cases for several aspects (e.g. regulatory, economic, related to compatibility issues) building-added systems could be — or even have to be — preferred to constructively-integrated ones.

The Bipv.tool is aimed to help building planners deal, in the design phase, with the great complexity of aspects that are involved in photovoltaic integration and to evaluate easily different options from all points of view, in a similar way to what occurred with environmental labeling. At the same time, as evaluation tool, its application to a number of case studies of PV use in buildings might also help compare different buildings, by taking into account not only the aesthetic quality of the system (which is basically linked to more qualitative and subjective considerations) in the overall building design, but also all other aspects involved (constructive, environmental, contextual…)[15]. However, in this sense, the process needs a series of very specific information regarding the case study building, involves over 140 requirements that need to be assessed singularly and some of which seem very difficult to be evaluated from the building planner (e.g. the embodied energy of the plant, which needs specific competences): this makes this evaluation process very complex, especially for an *ex-post* assessment of case studies.

3.2.4. Italian Energy Service Manager (GSE) Guidebook for the Acknowledgement of Architectural Integration

Italy can be considered as a best practice when it comes to incentivizing PV energy. Indeed, it has become one of the world leaders in terms of PV power installed also thanks to a very wide program of incentives[16] called "Conto Energia", active from 2005 until 2013. Conto Energia was the name of a program of incentives for the electricity generated from the sun by grid-connected PV systems, managed in Italy by the Energy Service Manager (GSE, Gestore dei Servizi Energetici). In particular, the incentives were distributed based on the amount of energy produced and sold, for the subsequent 20 years, at a preferential feed-in tariff to the National grid.

However, it must also be noted that the program of incentives has already expired, having reached too rapidly the maximum admissible amount of incentives. This is a not necessarily good news, because it is true that nowadays the cost of a PV plant has dropped significantly and that subsequently standard PV does not need massive incentives as before, but instead more complex building integrated PV solutions and new PV technologies still do. Conto Energia has recently been replaced by Conto Termico, focusing on solar thermal installations and, more in general, on the energy optimization of the building stock so that BIPV may still be incentivized in some ways, as a solution for the achievement of the energy efficiency in buildings.

For the purposes of this thesis, Conto Energia is of relevance for having recognized, for the first time in Italy, the Architectural Integration of Photovoltaics, in particular, with the 2nd Conto Energia (Italian Ministerial Decree no. 90 of 19/02/2007). The Decree was thought to foster and subsidize the spread of PV in Italy, favoring through premium incentives, in particular, those applications that could be considered as architectural integrations, referring to both buildings and urban equipment.

GSE elaborated a guidebook (GSE, 2007) of the installations acknowledgeable as architecturally integrated according to Conto Energia, containing qualitative and quantitative indications regarding what makes a PV installation eligible for the premium incentives specifically addressed to Architectural Integration example.

Among the aspects that were considered for the acknowledgement of architectural integration of a PV systems, the GSE guidebook individuates the dimensioning of the system — not only in terms of electricity production, but also in relation to building proportions —, the adequacy of its positioning, its visual impact and integration with the rest of the construction (alignment, coplanarity of elements).

In case of Partial Architectural Integration — i.e. where PV modules are mounted on buildings or on urban equipment elements without substituting their constituent material (GSE, 2007) — the following installation typologies are admitted in the Decree (cf. Annex 2):

- stand-off PV plants on flat roof, when the latter is provided with perimetrical balustrade whose height (H_P) is bigger than that of PV panels median axe (H_M) (Figure 3.2, case 1);
- PV systems that are coplanar to the surface they are installed on, without substituting it or parts of it (Figure 3.2, case 2).

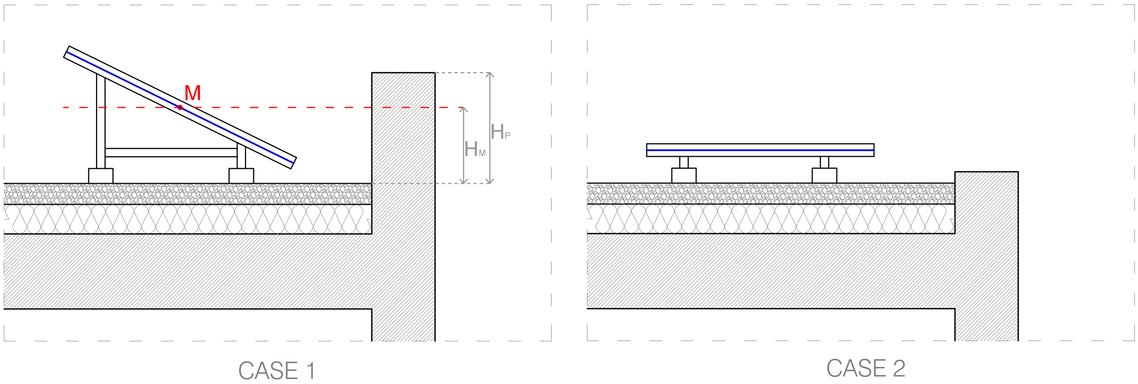


Figure 3.2 - Installation typologies admitted as Partial Architectural Integration according to GSE guidebook (re-elaborated from GSE, 2007)

The first of the above typologies basically corresponds to a situation where solar panels result hardly visible from outside the building due to the height of the perimetrical element in relation to that of the panels. Taking into account the second typology proposed, the GSE guidebook also reports — along with a series of examples, useful to illustrate what is taken into consideration for the architectural integration — other recommendations, such as: reducing the supporting structure of the PV system to the minimum possible thickness; avoiding that the panels protrude from the edges of the surface they are installed onto. In this regard, it is important to note that the coplanarity between the modules and the building surface and the "respect of the lines" of the surface where the modules are installed are acknowledged as criteria for a good integration also in other works (Zanetti et al., 2010)[17].

In the case of Total Architectural Integration — i.e. where PV modules substitute conventional building materials — technical and aesthetic aspects of PV components and of building envelope are balanced, without compromising their respective functional characteristics. The PV module becomes an element of the construction, whose characteristics (shape, dimension, colour, possible semi-transparency) might help provide value to the whole building.

Ten typologies of Total Architectural Integration were defined and had the right to have access to the premium incentives defined by the Decree:

1. *Modules substituting cladding materials;*
2. *Modules integrated into canopies and pergolas;*
3. *Modules substituting transparent surfaces;*
4. *Modules integrated into acoustic barriers;*
5. *Modules integrated into lighting elements and advertising sign;*
6. *Modules integrated into brise-soleil;*
7. *Modules integrated in railing and parapets;*
8. *Modules integrated into windows;*
9. *Modules integrated into shutters;*
10. *Modules installed as façade or roof cladding element.*

Among the recommendations, depending on the installation, GSE underlines the importance of studying specific systems for the grouping and hiding of the electrical connections as well as of designing carefully the linking elements between the PV system and the other building elements in order not to compromise the functionality of the building. When it comes to the aesthetic "performance" of the integration, the guidebook states that the PV system must fit harmoniously to the architecture of the building (GSE, 2007), without providing specific criteria in this sense.

It must be said, however, that the scope of the GSE in its indications was to give some as objective as possible parameters to define which types of installations and which products could be subsidized according to Conto Energia, but not to guide building designers and architects towards the highest architectural quality. When reporting a series of existing examples of PV integration eligible for the premium incentives, mainly standardized solutions can be indeed seen in the GSE guidebook.

All PV systems that did not refer to the two above introduced definitions were not integrated and had the lowest incentivizing tariffs; plants partially integrated in buildings had an average tarif, whereas the totally integrated systems were incentivized with the highest tariffs. This means that multi-functionality of an installation is fostered and awarded, being acknowledged as an important element for the attainment of successful integration results. The 2nd Conto Energia also awarded the use of PV in a building coupled with other energy efficiency measures, through the definition of an additional specific premium incentive.

According to Scognamiglio (2009) by proposing a number of possible typologies of integration — which in facts corresponded to the effective use of PV pursed in Italian buildings — GSE basically reduced the possibility of recognizing novel architectural solutions for PV integration that did not recall to the above-mentioned typologies.

Several interesting examples of architectural PV integration, not belonging to the "scheme" proposed by GSE — would not have been identified as either partially or totally integrated (Photos 3, 4) and would not have had access to the incentivizing policies of the

Photo 3 - Added Photovoltaic system on the façade and roof of the Sierra Bonita Affordable Housing, West Hollywood, Patrick Tighe Architecture, 2010

Photo 4 - Added PV system on the roof of Solar Townhouses, Freiburg-Riesefeld, T. Spiegelhalter, 1998

Decree, despite their qualities. In this sense, they would have been classified as not integrated and, practically, considered just like PV modules placed on the ground or PV panels simply juxtaposed to a building roof or façade without any care.

Overall, Conto Energia had the merit of having introduced and valued, for the first time in Italy, the relevance of the use of building surfaces to install PV and generate electricity directly where it is consumed, trying to avoid solar farms and installations that had really nothing to do with the buildings they served. Since 2007, premium incentives have been awarding partially or totally integrated solutions, but the repertoire of possible applications proposed by the Decree and by GSE guidebooks — that corresponded de facto, besides some exceptions, to the ways PV have been mainly integrated in Italian buildings — did not push for novelty of BIPV concepts, technologies and components.

3.3. Considerations

The definition of the architectural “quality” of a PV installation on a building is a very debated theme, which intersects aesthetic, functional-constructional and energy-related aspects. Differently that a simple installation of (BI)PV products, we can say that a well-designed architectural integration of PV should result from a synthesis and a balance between those aspects. It is not sufficient to install in a technically correct way a multifunctional BIPV product as part of the building fabric: many times BIPV products have been used, but that has not necessarily meant that a solution of high architectural quality has been achieved (Kaan 2009).

It could be interesting, in this sense, to cite the 2006 renovation of the Phare de Poulains in the island Belle-Île-en-Mer (France). Here, the former Eternit panels covering the roof of this lighthouse — listed in the “Inventaire général du patrimoine culturel” of France — have been replaced by multifunctional PV panels, integrated constructionally through the use of

Photo 5 - Phare de Poulains, Belle-Île-en-Mer (Sauzon), built in 1867, renovated in 2006: view of the building-integrated solar plant of 3 kW

a structure manufactured by a French company, called CLIPSOL[18]. The technical and constructional quality of this installation, providing this quite isolated building of a 10-day energy autonomy, have been widely acknowledged. On the other hand, the blue and highly reflecting solar panels with wide light-coloured framing altered the perception of the building, resulting as visually alien rather than integrated elements with respects to the building. The choice of a different colour for the panels and of a matte surface finishing, more compatible with other building material, as well as the pursuit of a higher uniformity in the appearance of this new energy-harvesting surface could have helped reaching a more balanced compromise among architectural and energy-related requirements, reducing the aesthetic impact of such installation (which turns out even more relevant, if we consider the listed status of the building), although probably reducing of some amount the output power of the system.

The above-presented works represent very useful references in this sense as they provide a series of criteria aimed at the evaluation of the integration of photovoltaics into buildings. Some (e.g. IEA:PVPS Task 7, IEA-SHC Task 41) have focused mainly on the architectural level by taking into account general aspects related to the formal aspect of a PV system (colour, proportions, modularity, etc.); some (e.g. BiPV-tool) have detailedly addressed the multiplicity of aspects involved in the integration of photovoltaics into buildings — morphological, energy-related, constructional, procedural etc. — by providing a multi-criteria assessment grid of evaluation of the PV systems into buildings. As especially the last paragraph helped understand, the idea of proposing some objective and omnicomprehensive criteria regarding the aesthetic quality of an integration is not really possible (and, in some cases, might also lead to inhibit the search for novel architectural solutions for the integration of PV in buildings, as Scognamiglio 2009 noted).

All aesthetic criteria are indeed linked to qualitative, interpretative and subjective considerations that need to be related to the specificity of each building and vary significantly case by case: for example, the context where the building is located, the characteristics of the building, the type of installation[19].

Also the multifunctionality of the installation, which is of great relevance as regards the economic, functional and technical aspects of the PV installation, can not be directly linked to the architectural result. Anyway, it is true that the use of multifunctional components, often specifically developed and optimized for use as building materials, can lead to an overall improvement of the formal quality of the integration that standard PV products often are not capable to provide. It can also generate several other benefits than simply added PV as widely discussed in the previous chapter at paragraph 2.2.1). However, at the same time, several built examples demonstrate that building-added systems can also result highly integrated from an architectural perspective. Indeed, regardless of whether the system is mounted on top of the already finished building envelope or integrated into it, «...*the most important thing of the architectural integration is to fit the elements harmoniously into an overarching visual concept. The question of additive versus integrated installation is secondary...*» (Krippner, 2003, p. 34). Having said that, it is not the purpose of this work to provide criteria for the assessment of the aesthetic and formal quality of PV in buildings, but rather to highlight some key-features that are considered relevant for the assessment of a PV integration. A critical study of built examples can indeed be useful to define some best practices.

3.4. Four Criteria for the evaluation of the PV Integration

Starting from the analysis of these experiences and from an in-depth study of built examples of PV use in buildings, involving both energy retrofits and new constructions, a list of features that are relevant to define the integration level of any example of PV use in buildings have been defined and four criteria for the assessment of the PV integration have been elaborated. Such criteria are utilized for the evaluation of the case studies that are analyzed and presented in the form of synthetic case-study sheets at the end of this chapter.

3.4.1. Design Strategy

The first integration criterion has been introduced in order to underline the role that PV has been attributed in the overall concept of a building, focusing on the morphological level of the analyzed PV installations and not (at least, not primarily) on its technical/constructional functions. In this sense, despite the great number of built examples of photovoltaic use into buildings and the significant variety of results achieved, five main design concepts can be outlined. Such concepts have been individuated by Weller et al., 2010 and have been resumed in this work, because they are considered representative of the possible strategies that can be adopted by building planners, while dealing with the use of PV in either new or retrofitted buildings. For the sake of completeness, these strategies and the corresponding definitions, as provided by Weller et al. (2010), are reported integrally as follows.

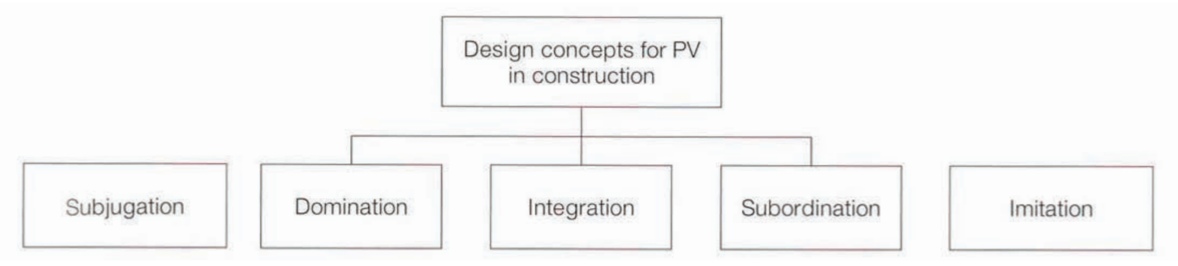


Figure 3.3 - Design Concepts for PV in construction (Weller et al., 2010)

Subjugation: «*…The term "subjugation" applies to those installations that are placed on or in front of a building without any architectural goals and whose sole task is to produce electricity. They may have been retrofitted to an existing building or their constructional and financial aspects even taken into account during the design phase. They use the building merely as a supporting medium and can be removed again relatively easily. If they are visible from public spaces, they frequently impair the appearance of the building. In such cases it is often the financial gains, sometimes an ecological consciousness, but certainly not the aesthetic effects that dominate the planning…*».

Domination: *«…When the solar technology has a decisive effect on the design of a new building, i.e. its orientation with respect to the sun, its volume and the configuration of the building envelope, then we speak of a "dominant" design. In many cases the PV installation contrasts markedly with the rest of the building envelope. These are frequently solutions with a certain degree of constructional integration, where the solar modules also provide some of the functions of the building envelope. Even retrofitted systems can be well integrated but nevertheless have a dominating effect if the PV installation has a distinctive effect on the appearance of the structure because of its colour, shape, size or arrangement…».*

Integration: *«…An integrated PV installation is in harmony with its building; the solar technology and the structure are equal partners in a symbiotic system. The solar panels frequently supply not only the electricity required for running the building, but also satisfy architectural and other functions of the building envelope, e.g. protection from the weather, sunshading. It is precisely these additional tasks that fuse the PV installation and the building into a virtually inseparable unit. Both aspects are so well tuned to each other that the whole is more than the sum of its parts. In the ideal situation, the PV installation not only merges harmoniously with the building, it also enriches the locality, the immediate urban or rural environment…».*

Subordination: *«…If the solar electricity system is hardly apparent because of its shape and size, its position with respect to the observer and public spaces, or its colour, it plays a subordinate role, and the building itself dominates. In this design approach the solutions can be very demanding aesthetically, especially the details, and their elegance is not evident at first glance. Such solutions are ideal for use in the heritage assets sector because they do not change the underlying character of the existing building, but rather demarcate old and new...».*

Imitation: *«…The imitating PV system tries to copy traditional forms of construction, replace their functions and at the same time add an active solar layer. Such approaches are frequently less than convincing, as is the case with solar roof tiles, for instance, because the imitation is seldom so good that the difference between copy and original is invisible. In addition, imitation obscures origin and purpose…» (Weller et al. 2010, pp. 40-41).*

Very often buildings presenting solar PV modules installed on their surfaces have been criticized for their lack of architectural quality (Krippner, 2003). In these cases, such unsatisfactory results are often due to a design approach that can be defined as subjugated, as in the above-cited definition. This approach is often focused only on the maximization of the energy production — often, at the lowest possible costs — and, for example, in the retrofit segment, often resulted into the indiscriminate installation of the solar panels (Photos 6, 7) onto any available building surface, regardless of the orientation and inclination of building surfaces as well as of their morphological characteristics (color, geometry, etc.).

Photo 6 - Example of *subjugation*: PV system retrofitted on a flat roof

Photo 7 - Example of subjugation: PV system retrofitted on a pitched roof

In the pictures, two retrofitted stand-off crystalline silicon PV plants on flat and pitched roofs are illustrated. The solar panels are oriented towards the best irradiation, regardless of the shape of the roof and of the building itself, even exceeding the eave and ridge lines in the pitched roof and the flat roof peripheral border. The installation definitely transformed and impaired the perception of the building and solar panels resul as extraneous elements to the construction. A more “sensitive” approach, with regard to the existing, could have been pursued by respecting the existing lines and shapes of the buildings, by giving up to some photovoltaic harvesting through the coplanar installation of the panels and by recurring to more adapted either building-integrated or added PV solutions in terms of shapes, dimension, colors (Photos 8, 9).

Photo 8 - PV systems on a housing district: the colour of solar panels merge with that of the roof cladding

Photo 9 - PV system on the roof of a single-family house, Hegenlohe, Tina Wolfe & Michael Resch, 2003

In order to exemplify the domination and subordination strategies, it is possible to cite as reference other two stand-off plants, installed during two significant energy retrofit interventions on the roof of two very different buildings: the Solgården in Kolding (Denmark); the Bauhaus Foundation Building in Dessau (Germany)[20]. In the first case, it is possible to speak of a dominant design: indeed, the large 90 kWp solar plant installed on the roof of the Solgården is a highly recognizable stand-off system, with a dominant effect on the overall appearance of the building. It is divided into four wings made of blue standard PV panels following the curved geometry of the building.

Photo 10 - Rear view of the BAPV system retrofitted on Solgården roof, Kolding

Photo 11 - View of the main façade of the Solgården, in Kolding, and of the "dominant" PV system installed on the roof

The plant has been designed (in terms of size, shape and arrangement, e.g. thin supporting structure made of racks and cables) to seem floating high above the roof, even from a distance. This dominant effect was specifically searched for, since this installation was a part of a demonstration project in the field of a Kolding renewal program, meant to exhibit the potential for PV in urban areas. Clearly, different reasons guided the energy renovation of the Bauhaus Foundation Building in Dessau (Germany). Being a listed building and a national monument, the objective of the intervention was to demonstrate how it is possible to provide an effective energy upgrade of a heritage building, without compromising its architectural language. This very discreet stand-off installation on the roof can be a perfect example of subordination design strategy: indeed, the PV system is made of frameless black

Photo 12 - The Bauhaus Foundation Building, Dessau, after the 2003 renovation

Photo 13 - Black micromorph silicon PV panels installed flat on the roof of Bauhaus Foundation Building, Dessau modules, with uniform and low-reflecting appearance, matching well with the former roof color, whereas the specially-designed supporting structure in aluminum is flat horizontal and thin, in order to avoid any disturbing impact on the Bauhaus architecture.

Subjugation and domination are two fundamentally opposite strategies: there is not an absolutely good or bad choice between them, but in the two above-cited examples they were adopted as the most fit to the declared objectives of the two interventions. In the first case, the goal was to communicate and demonstrate solar energy potential and, therefore, a highly-recognizable and dominant solar plant was designed to that purpose; in the second, the goal was to combine building energy upgrade with respectful heritage conservation and, as a result, a subordinated design was preferred.

The imitation strategy is close to the subordination strategy, but one significant difference may be highlighted among the two: the subordination strategy is aimed at the reduction of the impact of PV into the overall building appearance, through careful design choices as well as specific selection of products and related accessories; the imitation strategy, instead, is aimed at making solar modules hardly distinguishable from traditional materials of construction. The typical example of this approach is related to the use of solar tiles, i.e. multi-functional products replacing the weatherproofing layer of pitched roofs and characterized by similar installation modalities. Despite the large offering of standard solar tiles existing in the market — in terms of colors, shapes, appearance — this approach found application mainly in the retrofit segment and, in new constructions, in more standard and ordinary solutions (Photo 14). In this sense, it is of relevance to cite Scognamiglio (2010) underlining how attractive the use of PV as building component is to architects and designers, who are interested to create recognizable images for sustainable buildings as well as to use PV as a sustainable, energy-producing and innovative building material, exploiting the potential of this technology rather than concealing it through the imitation of other materials.

The choice of one design strategy or the others may depend upon several factors (i.e. the context of the installation, the characteristics of the involved building — be it newly-constructed or retrofitted —, its function, and so on…).

Photo 14 - Example of solar tiles (by Industrie Cotto Possagno) installed as finishing layer of a pitched roof

Photo 15 - PV slates integrated in the roof of Power House at Royal Gunpowder Mill, Waltham Abbey

For example, the characteristics of the context where the building is designed are of great relevance. In a historical centre, a strategy aimed at the maximum “discreetness”[21] of the PV system (subordination) could be pursued or required to the designer of the building, for reasons related to the search for compatibility between new and old and respect of the existing, especially in renovations and restorations. In many of these cases, the regulatory framework even imposes restrictions and guidelines, which can lead designers to opt for one strategy — that can be e.g. subordination or either imitation — and to exclude others possible strategies for PV use in buildings. In this regard, for example, Reijenga (2003) underlined how an invisible PV system might result more appropriate than a visible one based on modern high-tech PV modules, especially in renovation projects with historic architectural styles. An interesting example in this sense is the refurbishment of the Power House at Royal Gunpowder Mill in Waltham Abbey (Photo 15) where multifunctional PV element with the appearance of the historic slates have been installed *discreetly*, as finishing layer of the renovated building roof, on two of the less visible south-facing roof surfaces, in order to be virtually invisible from the ground (PRT, 2010).

In this field, it is of relevance to mention the renovation and energy upgrade of a building of the beginning of 20th century in the historical centre of Copenhagen (Christianshavn district), where a new prototype of BIPV roof panels has been specifically developed and integrated to replace the former roof tiling (Photo 16). This intervention, developed by a multidisciplinary team called Energi+[22], successfully addressed its objective to serve as a demonstrative project about the use of solar energy on ancient buildings worthy of preservation, also replicable in other contexts. After the implementation and test of different solutions, involving also 1:1 mockups, the final solution consisted of black crystalline silicon panels, reproducing the color of the replaced roof finishing. The rest of the roof surface is covered with matt black panels in the same module as PV panels. It is not possible to talk either of imitation or subordination, but rather of an integrated design approach where technological, energy-related and architectural aspects found the right balance, allowing for the first solar roof integration in the historical context of Christianshavn[23], contextual to the energy performance upgrade of the building.

Photo 16 - Views of the Building in Andreas Bjørns Gade, Copenhagen, before (*left*) and after (*right*) the energy renovation of the roof, designed by Energi+, 2013

The imitation strategy in many cases could also derive from a specific customer's request of "not recognizability" of the PV solution. In many cases, contrarily, customers ask for highly-visible PV installations, able to be a medium for exhibiting their sustainable image leading architects to adopt domination design strategy: this often occurs in commercial buildings, e.g. Zara Store in Cologne (Photo 17), or either industrial buildings, especially those owned by PV manufacturing companies, e.g. Xeliox Energy Labs in Bergamo (Photo 18). In the first building, the photovoltaic modules have a distinctive effect in the appearance of building structure, due to their shiny blue and glimmering appearance, covering most of the façade surface with the aim to recall pedestrians inside the shop.

In Xeliox Energy Labs, the particular configuration of the PV-integrated main façade was thought to maximize energy production performance as well as to become a landmark able to capture public attention and manifest building's sustainability: it is indeed the first Italian industrial building having achieved the *Classe A* certification[24]. In particular, this south-east experimental façade is fragmented into rhombus-like elements, hosting solar thermal as well as PV modules, slightly tilted in order to find an optimum installation; moreover, the double-curved configuration was specifically designed to maximize solar yield and compensate for non optimal south-east exposure. Solar technology, in this case, has a significant effect, as regards not only building appearance (as in the previous case) but also building envelope shape and configuration as well as its orientation with respect to the sun. However, it must be highlighted how, without a formal control, the will to exploit all benefits related to the maximisation of the energy production from PV as well as to benefit from the sustainable and "green" image related to this technology can lead, for example: to install PV plants that are completely misproportioned compared to the building where they are installed; to focus only on products with maximum efficiency values regardless of their appearance as well as of their compatibility with the contexts of installation, with the other building solutions and, last but not least, with the requirements they are called to fulfil; and so on… This can generate unsatisfactory results on the architectural level and has led in many cases domination to cross over into subjugation (Photo 19).

Photo 17 - The new façade of the Zara Store in Cologne, Architekturbüro Feinhals, 2003

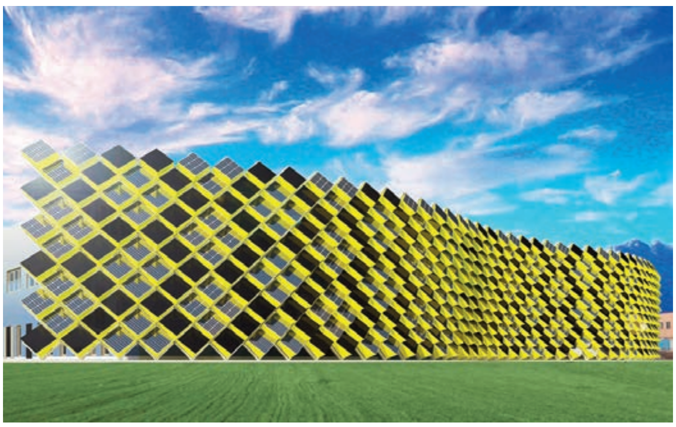


Photo 18 - View of the innovative façade of the Xeliox Energy Lab, Marco Acerbis, Bergamo, 2008: project render

Contrarily, in several cases, part of the photovoltaic production has been "sacrificed" in favour of a higher level of architectural and environmental quality of the solar system.

In this sense, a successful integration example can be recognized in the so-called "Solar Canopy" of the California Academy of Sciences (2008), located in the Golden Gate Park in San Francisco and designed by the Renzo Piano Building Workshop in collaboration with Stantec Architecture[25]. The "Solar Canopy" (Photo 20) is a glass and steel horizontal divider, running across the whole perimeter of the building, originally meant to integrate natural elements such as trellis. The idea of integrating photovoltaic modules on it revealed as a big challenge in the design process, as Jean Rogers, Sustainability Consultant for the project from Arup, remembers: «*…we've really got to go through literally years to finding the right photovoltaics that could be integrated, provide shading as well as daylight and wouldn't create that cave-like effect as you approach to that entrance…*»[26]. Each of the 720 custom-made glass modules — providing approximately 10 percent of the Academy's electricity requirements — is coupled with at least one glass element, screen-printed with a white-colored pattern replicating that of silicon wafers. The pattern is more or less dense, according to the position in the building and to the light level required below.

An approach oriented towards the maximisation of the photovoltaic production could have brought designers to cover the whole surface of the canopy in opaque cells, probably more than doubling the electricity production of the system. At the same time, this would have altered the perception, livability as well as the architectural and environmental quality required for the spaces outside the building, below the "Solar Canopy". This has not prevented the "Solar Canopy" to become a key element for the achievement of LEED Double Platinum Rating from the US Green Building Council by the California Academy of Sciences. By the time of its construction, this building became the largest public building having reached this rating. Its whole design process, indeed, has been oriented towards the maximization of the environmental quality and the minimization of the environmental impact of the building, during both construction and management stages, and this solar integration is an *inseparable part* of it.

Photo 19 - Sundial Multi-purpose Building, Dezhou, China, 2009: fan-shaped roof with around 5,000 square meters of PV panel installation

Photo 20 - California Academy of Sciences, RPBW, San Francisco, 2008

The student housing building at the harbour of Aarhus (Denmark) by Arkitema Architects (Photo 21), is another interesting example of an innovative approach for the architectural integration of photovoltaics. It is at the same time the demonstration of how an integrated approach for the installation of solar modules onto a building can be not only a way to enhance its energy efficiency, but also to generate positive relapses on users' comfort and to valorize and mark its appearance.

This 11-storey building was selected after a public competition: the clients' requirements regarding energy efficiency and renewable energy utilization in the building to be designed were very demanding. The peculiar solar installation on the south-west side of the building came out in the design process as a way to reach the energy self-production targets established by the clients. Indeed, the installation of solar panels on the roof of the building was not sufficient to achieve such targets, also due to the particular configuration of the building, which is characterized by a prevailing vertical development and thus with a limited roof surface. As a result, Arkitema Architects proposed these multifunctional external vertical dividers, constituting the elements of protection from falls of the balconies of the south-exposed façade as well as a further renewable energy supply source for the building. Each of these 23 elements is constituted by 6 frameless semi-transparent panels in monocrystalline silicon arranged in the shape of a square, uniting the balconies of two different floors. Each frameless PV panel is secured, by means of point fixing along the edges, to a horizontal support structure in aluminum. This is in turn anchored to the vertical steel hollow elements that connect the load-bearing cantilevers of the balconies. Besides providing protection from falls, these semi-transparent PV-integrated elements protect the indoor spaces from excessive solar radiation and from the very strong wind blowing in the area where the building lies. Additionally, the break in the flatness of the surface of the façade, resulting from the presence of the projecting balconies and of such multifunctional external partitions, could also help reduce the strength developed by the wind blowing on the building façade. The composition of these square elements, disposed along the building façade according to an irregular and staggered distribution, gives birth to a peculiar expression that represents

Photo 21 - Student housing building at the harbour of Aarhus, Arkitema Architects, 2012

(left page) View of the multifunctional PV elements installed as balcony parapets on the south-west façade of the building;

(right) closer view of the multifunctional PV elements

building main characteristics and integrates *coherently* with the play of staggered squared frames and windows, characterizing the rest of the building envelope. The photovoltaic integration allowed designers to meet the energy efficiency targets needed to participate to the competition, but most of all became an irreplaceable and unique element of valorization of building appearance[27].

3.4.2. Multifunctionality

It has already been widely discussed how, when considering a PV integration, multifunctionality is a fundamental aspect to consider especially as regards the issues related to economic aspects in the construction of a building, and also for other aspects concerning the functionality of the building skin (Krippner, 2003). The Multifunctionality represents the possibility of a PV module to be used and installed as a technical element of the building envelope, thus physically replacing one or more technical elements and/or functional layers of the building fabric and providing one or more building functions as defined in the CPR 305/2011.

It is possible to state that the "integration level" will be higher, if also a technical-constructional integration of the PV element as components of the buildings is occurring. Especially when speaking of new buildings, the multifunctional use of BIPV products might lead to several advantages (in terms of materials, construction works, etc.) that have already been widely discussed. However, it should also be noted that the physical integration of PV into the building system is not always the best solution. Considering especially the retrofit segment, for example, it is neither sustainable nor cost-effective to replace a perfectly functioning roof with a multi-functional PV installation; differently, if a roof renovation is required (e.g. as in the building in Copenhagen described in paragraph 3.4.1, p. 115), the possibility of a multi-functional installation — allowing, with one single operation, for the renovation of the technical element and the installation of the PV system — should be evaluated carefully by taking into account costs, regulatory issues[28], and so on...

In both cases, regardless of whether the system is mounted on top of the already finished building skin or integrated into it, the added value related to formal characterization of the building is another important function, a non-technical one, that can be provided by the PV modules and that is relevant for the definition of the "integration level" of a PV installation. Having said that, two sub-classes have been distinguished under the multifunctionality criterion:

- *Multi-functional building and PV element:* occurring when, in case PV modules are removed, the original function of the technical element/functional layer is no longer met and the substitution of PV with adequate technical elements/functional layer is thus needed;
- *PV components with active part in building image definition:* occurring when PV module is an active part in building image definition, meaning that materials are visible and aesthetic potential of the technology is explored.

3.4.3. Other Bioclimatic Features

The integration of multifunctional BIPV components as technical elements of the building envelope has been widely recognized as a multi-benefit strategy for the construction of Zero Energy Buildings (ZEBs) and for the energy retrofit of the existing building stock. Indeed, when such solutions are appropriately incorporated into building design, they can provide several functions and benefits other than the electricity production. The third integration criterion takes into account, in particular, the benefits that the multifunctional use of photovoltaics can produce for the improvement of bioclimatic control capability of the building envelope and thus for the optimization of building energy efficiency.

This aspect — which has already been highlighted in different literature studies such as Scognamiglio (2009), Bonomo & De Berardinis (2012) — is based on the consideration that solar modules, besides producing clean electricity, can also "passively" contribute to the reduction of the energy consumption of buildings and to the improvement of users' comfort. In this sense, the functions supplied by the PV module for the passive improvement of building energy efficiency can be classified into two main options (that can even co-exist):

- *Passive exploitation of conversion heat,* which refers to the possibility to exploit the conversion heat that is developed on the rear of the modules in order to activate passive mechanisms of ventilation and/or heating;
- *Solar and thermal protection,* which refers to the possibility to optimize/control/regulate the exchange of solar and thermal energy across the envelope through the correct design of the PV installation (e.g. daylight control provided by PV modules installed as either fixed or movable louvers and brise-soleil; sunshading provided by semi-transparent modules integrated onto transparent and/or translucent elements of the building envelope; etc.);

It is possible to individuate several examples of both new and retrofitted buildings, where such bioclimatic potential of BIPV is exploited by taking into account not only the aspects related to the choice and design of the most adapted PV components, but also the way they are installed (mounting system, integration with different functional layers and elements of the building fabric, i.e. fixed or movable louvers, windows, etc.).

3.4.3.1. Passive Exploitation of Conversion Heat

It has already been widely underlined how the operating temperature of solar modules can reach very high values, even above 70°C depending on several factors. Indeed, only a portion of the absorbed solar energy is converted into electricity — according to modules efficiency, which hardly ever overcomes 20% — whereas the rest of this energy — thus, more than 80% — is converted into heat, increasing the temperature of the solar modules. This overheating can generate several issues, especially in first-generation technologies, not only in terms of energy productivity, but also because such high temperatures can generate situations of summer discomfort, particularly in warm climates, as well as thermal stresses on the solar modules with potential negative effects on their durability.

Due to the above reasons, it is a common as well as highly recommended praxis to foresee the possibility of rear ventilation to exhaust part of this heat developed contextually with the PV conversion, especially for crystalline silicon modules, where such overheating issue is particularly relevant. On the other hand, the possibility to exploit and redirect this heat storage can be a way to improve passively indoor comfort conditions, especially in cold climates.

An emblematic example in this sense can be encountered in the multifunctional glazed façade retrofitted on the south-west orientation of the Kollektivhuset[29] in Copenhagen (Photo 22). This façade was built to cover the existing balconies, providing weather protection as well as noise insulation from the high-traffic road in front of this residential building for disabled tenants. The balconies were contextually enlarged in order to facilitate the access to people in wheelchair that many of the occupants use. The indoor/outdoor spaces resulting from this retrofit operation can be opened in summer and totally closed in winter by means of sliding window systems. Semi-transparent mono-crystalline panels were installed as parapet of these spaces and each of them is provided with a colored glass pane that can slide in order to close or open the spaces behind them.

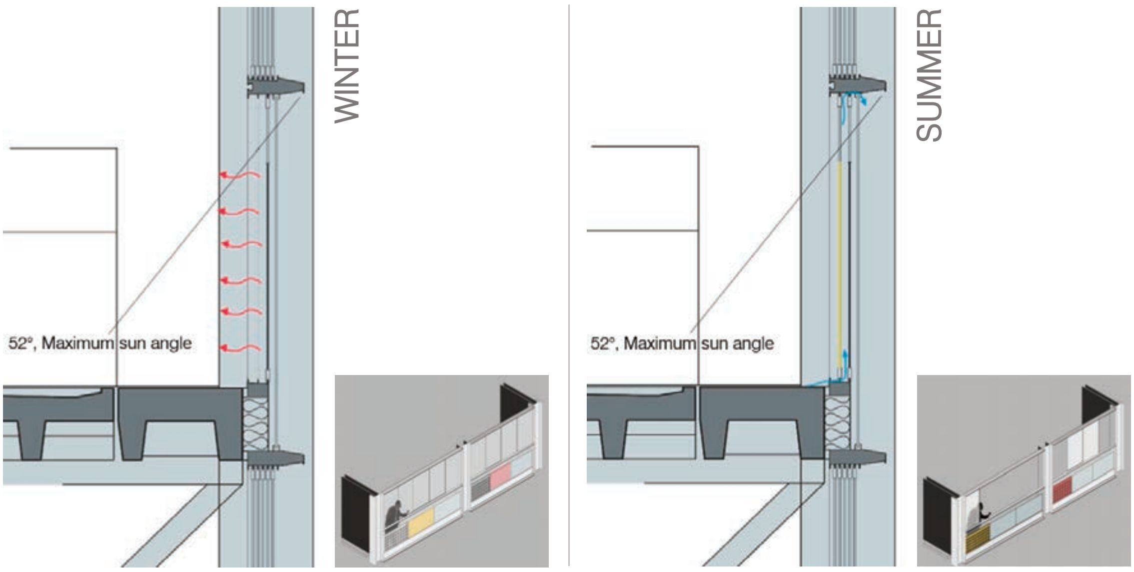


Figure 3.4 - Scheme illustrating the winter and summer functioning of the glazed balconies at the Kollektivhuset, Copenhagen, Domus Architects, 2002

Photo 22 - Kollektivhuset, Copenhagen, Domus, 2002. View of the new glazed façade after the retrofit

Photo 23 - (*right page*) Solcellegården in Aarhus, Arkitema Architects, 2008. View of the PV-integrated façade

Therefore, in summer, the rear of the panels can be closed and the heat developed from the PV conversion is let out of the façade by means of appropriate ventilation openings at the top and bottom of the profiles around the PV panels; whereas, in winter, the conversion heat can be let in and be used to increase the thermal comfort and livability of the spaces placed immediately beyond the façade.

This passive heating/cooling strategy — which has been considered carefully also to avoid the re-radiation of a large fraction of heat directly to the legs of wheelchair-users — also confers a multicolor and variable look to the new façade, improving the appearance of the building, in addition to all the above-mentioned benefits.

Such innovative and successful example was the result of a close collaboration among the PV manufacturer (Gaia Solar, DK), the electrical designers (Esbensen Consulting Engineers, DK) and the architects (Domus Architects, DK), which have worked together to build one of the most visible and well-known demonstration projects with building integrated photovoltaics in Denmark[30], perfectly integrating and solving architectural, constructional and energy-related aspects[31].

Another Danish example demonstrates, with a completely different solution, how it is possible to exploit passively the heat developed on the rear of PV modules during operations in order to optimize the comfort conditions and the energy performance of a building: that building is Solcellegården in Aarhus (Photo 22, p. 123), by Arkitema Architects.

Solar panels are installed as part of a "solar wall" system designed to produce electricity, while cladding the building and preheating the air that is then drawn into the indoor spaces in order to reduce energy consumption and improve thermal comfort.

As it is possible to see from the Figure 3.5, the solar panel is the external cladding element of the "solar wall" system; behind it, a cavity separates the panels from the internal wall, which is characterized by an absorber (1.5 mm thick black aluminum plate), an insulation layer and vapor barrier. The cold air is let enter behind the solar panel through a longitudinal air gap at the bottom of it. The air layer behind the solar panel is preheated by the direct or

diffuse radiation of the sun as well as by the convection of the heat emitted from the absorber plate and that coming from PV conversion. Then the preheated air is led into the apartments through fresh air valve, placed in the upper part of the rear wall.

The solar installation, in this project, is part of the energy concept of the whole building and participates actively to the optimization of indoor comfort conditions, reducing the energy consumption of Solcellegården while producing part of the electricity for the satisfaction of its energy requirement.

It is also worth to underline how the solar panels, with their staggered disposition, alternating with the glazed openings, have also a determining role into the expression of the building envelope integrating into a typical Danish urban landscape dominated by brick façades[32].

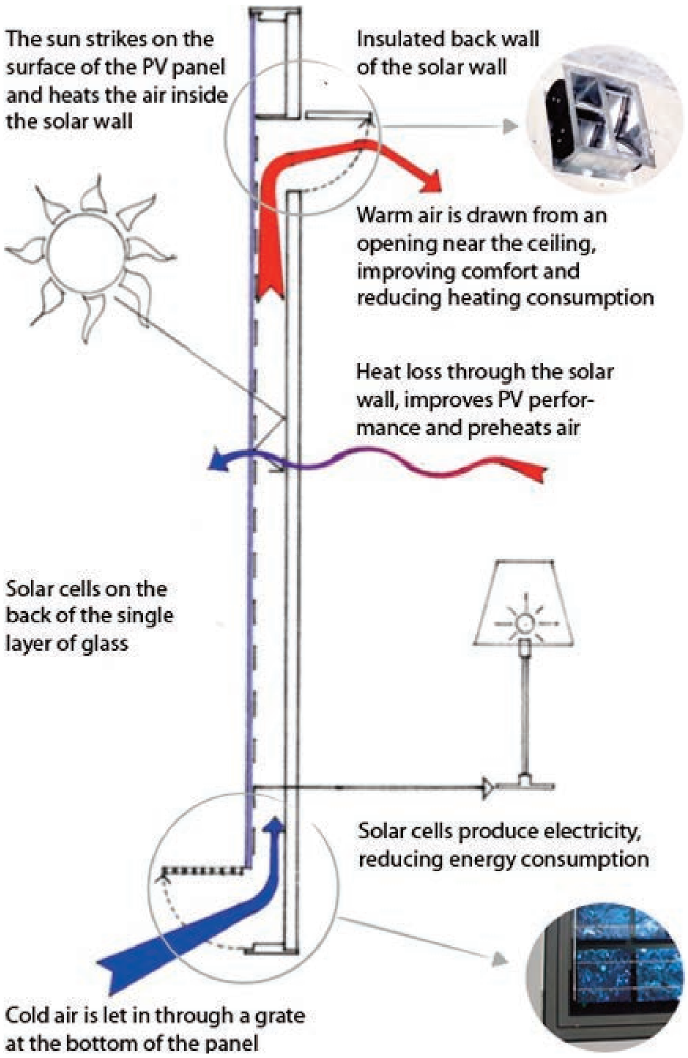


Figure 3.5 - Functioning of the "solar wall" of Solcellegården, re-elaborated from the competition drawing

Another built example that is worth to mention, in this field, is the innovative façade crowning of Concordia University's John Molson School of Business (JMSB) building in Montreal (Photo 24), implemented by a team from NSERC Solar Buildings Research Network (SBRN)[33]. It represents the first application of SolarWall® BIPV/T: a commercial solution for combined solar air heating and electricity production, developed by Conserval Engineering Inc[34]. The aim of this solution is to maximize the potential related to PV as a viable renewable energy solution for buildings by exploiting the conversion heat, which — as already underlined — normally is lost and provides no value to the owner, but rather causes a drop in the electrical output of the system.

The SolarWall® BIPV/T technology (illustrated in Figure 3.6) is characterized by specifically designed PV modules[35], which function as elements of electricity production as well as finishing layer and are mechanically fixed to a perforated metallic absorber. This latter has the function to let the cold air from outside enter inside the cavity placed behind it and in front of the insulation layer of the wall. The cold air is then heated by the thermal energy exceeding from the PV conversion as well as from the solar radiation striking on the façade and channeled by means of a ventilation element and a fan inside the building. This has positive effects not only as regards the indoor thermal comfort but also for the cooling-off of the PV modules, resulting into higher energy output. In the specific demonstration case, this technical solution provides a significant enhancement of the solar efficiency:

- 24.5 kWp of photovoltaic power installed;
- 75 kWp of heat by fresh-air solar heating with a 288 m^2 SolarWall® system, preheating up to about 15,000 cfm of fresh air (about 7 m^3s).

The first example can be considered as a "sun space", the second and the third as "solar wall" solutions. Both are passive solar techniques (briefly described in Chapter 1) that can be easily matched with active solar devices both in the field of new construction and retrofit. As shown in the examples above, PV can be exploited to add the benefits related to the electricity conversion and to help enhance the efficiency of these "passive" solutions thanks to the conversion heat.

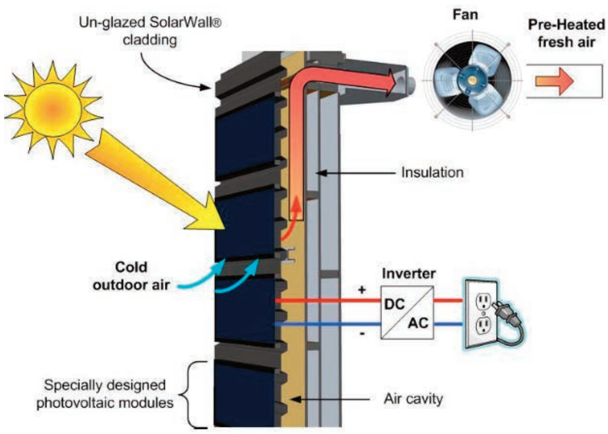


Photo 24 - JMSB Building in Montreal, 2013
Figure 3.6 - JMSB PV/T Process Flow Diagram (NSERC, 2012)

3.4.3.2. Solar and thermal protection

Several examples of both new and retrofitted buildings demonstrate how solar modules, multi-functionally integrated into the building technical system, can be useful to optimize/control/regulate the exchange of solar and thermal energy across the envelope, besides producing clean electricity.

For example, in this field, the following possibilities can be outlined:

- solar control provided by BIPV modules installed as either fixed or movable sub-components of canopies, shutters, louvers and brise-soleil;
- sun-shading/day-lighting provided by semi-transparent BIPV components integrated as transparent and/or translucent elements of the building envelope (which in general need to be provided of adequate thermal insulation performance or, at least, be coupled with other functional layers and/or elements able to supply it).

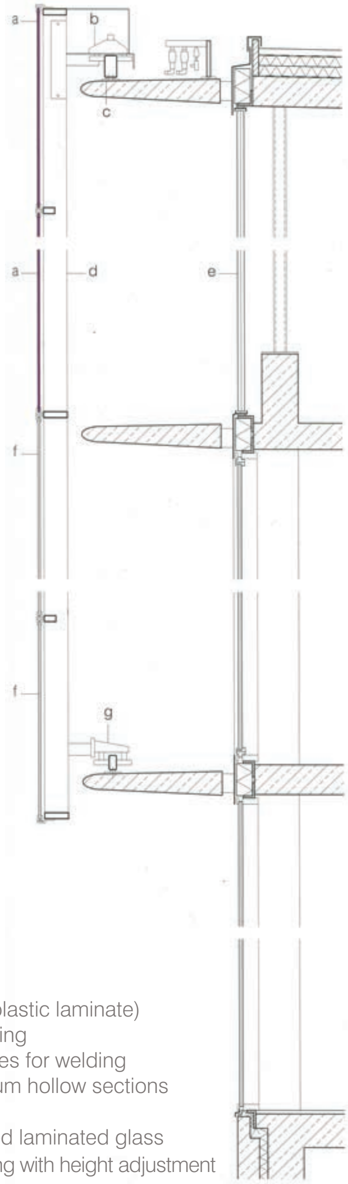
As regards the first of the above-listed possibilities, a great variety of more or less standardized solutions exists in the market, regarding both BIPV components and technical systems for their installation as well as for their automatic or manual control, in case of movable solutions. As already underlined in the previous chapter, solar energy absorption and sun-shading function match perfectly one another and the integration of solar modules as sun-light attenuation layers and/or elements of envelope and/or external dividers has found application in several buildings.

Among the built examples, the following two are considered particularly relevant for the way the PV system turns out to be a relevant and integral part of the energy concept of the building (and not exclusively because of its electrical production): the first is the EWE Arena (2005) in Oldenburg, Germany, designed by 'asp' architekten; the second is the Plus Energy Home, prototype of net-zero energy house for the Solar Decathlon (2007), designed and implemented by Darmstadt University of Technology.

The EWE Arena (Photo 25) is a sports building, characterized by a circular plan. It houses a central 4,000-seat hall for matches — and even concerts, due to the optimum acoustics — and all related service areas are distributed around and below it. The peculiarity of this building is related to the special sun-shading element designed to provide the adequate solar protection to the circulation spaces disposed on the perimeter of the building. Such spaces are entirely cladded in glazing and, without an appropriate shading system, would have been subjected to severe summer overheating as well as glare phenomena. In order to prevent this to happen, designers defined a photovoltaic movable sun-shading element, 36-meter long and 6.7-meter high, with a circular arc shape concentric with respect to the building. A number of 72 opaque photovoltaic modules in monocrystalline silicon laminated onto glass are installed, by means of point fixings, on the upper part of this sun-shading system. The lower part is characterized by just as many screen-printed glass panes, equally shaped, dimensioned and fixed to the curtain wall aluminum support structure, which is in turn connected to the building structure (Figure 3.7). During the day, this sun-shading element

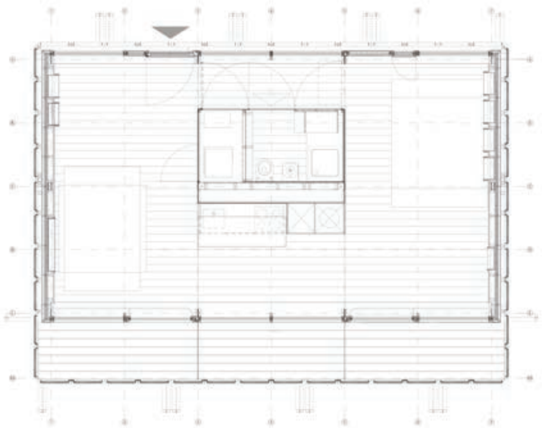
is able to move along a stainless steel rail fitted around the southern half of the building and to follow the sun's path by covering an angle of approximately 200° from east to west (at 15° per hour speed). This system acts like a sun-tracking PV system, perfectly integrated both functionally and aesthetically into the building. Besides optimizing both thermal and visual comfort conditions inside the building at each time of the day, indeed, this solution can also maximize the PV production. The measured electrical performance of this unique PV system significantly exceeded the expectations by generating, already in the first 6 weeks of operation, 50% of the estimated annual production[36].

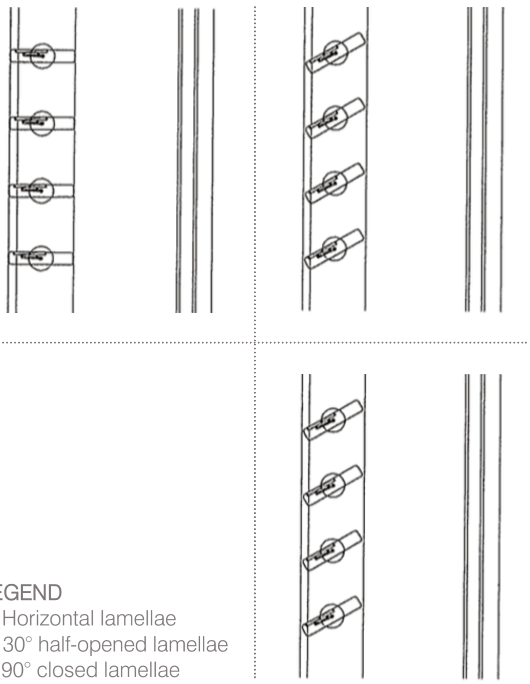
The benefits deriving from photovoltaic generation and sunlight protection are combined and maximized in this project as well as integrated into a coherent overall architectural concept, which was also awarded in several competitions regarding solar energy and architecture[37].



LEGEND
a. PV glass (glass/plastic laminate)
b. Upper roller bearing
c. Annulus with plates for welding
d. Frame of aluminum hollow sections
e. Glass façade
f. Silk screen-printed laminated glass
g. Lower roller bearing with height adjustment

Photo 25 - EWE Arena, 'asp' architekten, Oldenburg, 2005: view of the façade-integrated PV system;
Figure 3.7 - Detailed vertical section of the façade and of the movable, PV-integrated, sun-shading element (Weller et al., 2010)





LEGEND
a. Horizontal lamellae
b. 30° half-opened lamellae
c. 90° closed lamellae

The Plus Energy Home (Photo 26) was designed by a multidisciplinary team from Darmstadt University of Technology for the third edition (2007) of the Solar Decathlon[38]. The optimum energy efficiency of this prototype house — awarded of the first prize at the competition — was obtained through a balance between passive measures for thermal insulation, natural cooling, solar gain and active systems. Also in this example, multi-functional modules are integrated into the building technical system and are used to optimize and regulate the exchange of solar and thermal energy between indoor and outdoor environments. In particular, the south-exposed side of the building is characterized by a buffer space that is placed in front of an entirely glazed façade. It can be totally closed or opened on its three sides according to the season and to the moment of the day by means of foldable louvers provided with PV-integrated and PV-activated lamellae. The 1,122 PV lamellae — consisting

Photo 26 *(left)* - Plus-Energy House, 2007 Solar Decathlon, TU Darmstadt, 2007: foldable PV shutters; *(right)* - Detail of the PV-integrated lamellae;
Figure 3.8 - Section of the three possible positions of the lamellae (www.solardecathlon.org)

of metal-embedded amorphous silicon plates screwed onto wooden elements[39] — are installed on the south, east and west sides of the building. The louvers covering the north side do not present any solar module. The lamellae can tilt automatically following the solar path and, as illustrated in Figure 3.8, according to three possible angles: 0° (horizontal lamellae, particularly useful angle for shading and PV harvesting in situations when the sun is high in the sky), 30° and 90° (vertical lamellae, particularly useful angle for closing the louvers and avoiding wind infiltration, with potential benefits in terms of thermal protection too). In order to avoid self-shading only a part of each element is provided with PV.

This buffer space presents also a semi-transparent PV roof made of monocrystalline wafers, laminated onto glass and perforated in order to increase the solar gain and the transparency, in order to let light and heat in (as in the second of the above-listed possibilities for bioclimatic exploitation of PV for solar and thermal protection). Besides optimizing visual comfort, louvers and lamellae help regulate passively also the exchange of the heat accumulated in the buffer space with the outside or inside environment for the achievement of the maximum comfort for users.

The system was awarded for its energy efficiency and novelty as well as for its successful architectural outcome. The PV-integrated lamellae on timber louvers, in particular, represent an outstanding architectural solution, with completely integrated interconnections and activation mechanisms as well as elegant appearance, achieved by means of a thorough design of the details. With regards to the five design strategies defined in the previous paragraph, such a "discreet" solution can be considered as an example of the "subordination" strategy and it could result particularly suited also for the installation in the energy retrofit of buildings, even in those contexts where a respectful attitude to the existing is required (e.g. in the field of the heritage asset).

The second of the above-listed possibilities for bioclimatic exploitation of PV for solar and thermal protection regards the architectural integration of Semi-Transparent Photovoltaic products (STPV) as technical elements of glazed façades and roofs as well as of spatial dividers outside the building envelope. Several STPV products specifically developed for this kind of installations are already on the market and the segment for BIPV glazing has been constantly growing. Quite often manufacturers provide a wide range of configurations in order to enable products to adapt to a wide variety of climatic contexts, building applications, and performance requirements (as defined by building designers and technical consultants)[40].

In this sense, each project that adopts one of these solutions should foresee a specific work in the definition of the characteristics of the photovoltaic modules and of the related installation systems, as regards their performance in terms of mechanical resistance, thermal insulation, light and solar transmission as well as electrical production, in order to find a perfect synthesis among energy-related, constructional and architectural aspects.

A remarkable example of this sustainable and systemic approach can be encountered in the project of the Sports Hall in Burgweinting (Photo 27) where a translucent multifunctional PV installation was specifically designed to integrate formally and constructionally into the building envelope and, at the same time, to optimize indoor comfort conditions.

The building is the extension of a school, has a rectangular plan and contains a gymnasium and related services. Each of the four façades of the building is divided into two parts: a continuous cladding made of timber slats laid horizontally at the base of the building and an entirely glazed surface on the upper part of the façades.

A multi-disciplinary team of engineers and architects as well as of researchers of the Fraunhofer Institute for Solar Energy Systems[41] has been involved to make the best possible use of the glazed crowning element running through all the perimeter of the building. The main issue regarded the south façade that, if not accurately designed in terms of light transmission, thermal insulation, sun-shading properties, would have compromised the comfort conditions inside the hall. After a number of software simulations[42] and studies of the context, the team came up with an energy efficient solution, involving BIPV glazed components.

In particular, 98 panels in polycrystalline silicon laminated between two panes of toughened glass were integrated as elements of double-glazing units (with krypton-filled insulating cavity) and used to contribute to the efficiency of the building, not only through the PV production. The 20-mm distance between silicon wafers has been calculated in order to guarantee the optimal level of natural illumination and avoid dazzling effects. The inner pane of the double-glazing is an 8-mm thick laminated safety glass with matt PVB interlayer able not only to provide the adequate mechanical resistance against ball impacts — as required in a sports hall — but also to scatter the direct light, to allow diffuse light and thus to improve indoor visual comfort.

Photo 27 - Sports hall in Regensburg, Tobias Ruf, 2004. View of the south-façade integrated with PV

Photo 28 - Schott Iberica Building, Barcelona, Torsten Masseck, 2008: view from the interior of PV windows

The inner surface of the outer glass pane is coated with a low-emission oxide, in order to reduce heat losses during winter and summer overheating. The U value of the PV glazing is 1.1 W/m^{2}K and the g-value is equal to 0.146.

The glazed elements on the other façades have also been accurately studied and each has been provided of a different glazed solution, openable for natural ventilation in some cases: from the highly transparent low-emissive glazing on the north side to the light-scattering glazing of the east and west façades, designed to avoid any glare effect inside the building and optimize also its thermal performance (Weller et al. 2010).

The frameless modules are fixed by means of light-coloured horizontal aluminum profiles, while vertical joints are thinner and dark-colored. This helps accentuate the horizontality of the façade — also suggested by the horizontal disposition of the timber slats cladding the base of the building — and confers to the building envelope a coherent language. As a part of this systemic approach, the photovoltaic system can be considered well-integrated also in architectural terms.

Also in the retrofit of the Schott Iberica Building, in Barcelona (Photo 28), semi-transparent BIPV glazing was installed in the south-west façade providing a significant improvement of indoor comfort conditions (besides, of course, the reduction in the electricity bills related to the use of PV). Before its 2005 renovation, the 5-floor staircase located on the south-west façade of the building was suffering from severe problems of overheating due to insufficient ventilation, lack of sun-shading and poor thermal behavior of its glazed elements.

Multifunctional BIPV panels[43], made of 10% transparent amorphous silicon thin-film applied on colored glass substrate, were installed as window infills, along with openable printed glass panes placed on the lower part of the façade. These substituted the previous fixed translucent glasses that used to generate unsustainable internal temperatures in summer (up to 50°C). Thanks to this installation, coupled by an optimized natural ventilation strategy, the annual energy consumption of the building dropped of about 8%. This demonstrated the potential energy-saving benefits related to the exploitation of the solar and thermal protection that can be provided by semi-transparent PV modules installed as technical elements of the building envelope. In actual facts, monitoring operations showed that the choice of a colored glass substrate — which has been related to considerations regarding the desired appearance of the retrofitted building façade — is linked to a certain increase of cells temperature (10-15 °C compared with a panel of similar characteristics with colorless substrate). This can lead to a decrease in PV performance (Masseck, 2006). However, amorphous silicon technology is characterized by a relatively low temperature coefficient (-0.20%/°C) and therefore this overheating does not produce a notable drop in the PV performance. Nevertheless, it is important to highlight that this aspect must be carefully taken into account in the design phase, when the characteristics of the BIPV module (substrates, subcomponents, and so on) are selected, also for reasons related to durability and thermal comfort of users.

3.4.4. Elements of Innovation

It is important to underline how the success of a lot of projects involving a PV integration often also lied in the novelty and unconventionality of the technical and design solutions adopted, often able to provide new and better responses to different building requirements.

Innovation has already been addressed as a criterion for a good integration of PV in some of the works described previously in this chapter (e.g. Schoen et al. 2001, Bonomo et al. 2011) and it is considered also in this work a relevant criteria for the evaluation of the degree of an architectural integration.

Elements of innovation can be encountered in solar modules design, in the characteristics of their installation (jointing/fixing systems, support structure, etc.) and/or in the integration concept, related to the overall building design and the three sub-classes to this integration criterion have been individuated accordingly:

- *Module Design:* the novelty regards module design and, for example, it can involve color treatment, finishing, pattern and/texture;
- *Module Installation:* the novelty lies in the way modules are installed and, for example, it can involve the technological as well as aesthetic characteristics of the elements used for the integration (jointing/fixing systems, support structure, etc.);
- *Integration Concept:* the novelty regards the overall integration concept, which can even involve “standardized” and/or “traditional” modules, and it lies in the relapses that the PV installation has on overall building energy performance as well as on the building image.

The innovation, especially in such a growing and evolving sector, has the power to: help the spread of new solutions to integrate PV into buildings allowing for new previously unexplored possibilities; boost the development of new products that can allow integrating PV where previously was impossible; foster the establishment of new practices and the replication of good examples for the design of both new and retrofitted buildings; push designers and planners to seek for innovation; open new scenarios for the applicability of PV in buildings.

In this sense, the Herne Academy is a very relevant example of the importance of innovation into the BIPV sector and of the innovation cycles it can generate: indeed, as also underlined by Scognamiglio (2010), this building, completed in 2000, made use of a decidedly innovative product at the time of its design and construction (i.e. double-glass modules with specific color, degree of transparency and dimensions, installed as infill elements of roof and roof-light systems). Also thanks to the impacts that such a big work can produce on an industrial level, this product after became a rather common PV component. Innovation indeed might in the end lead to a growth of the BIPV sector with all related economic benefits and to a wider spread of PV into buildings with all corresponding benefits in terms of renewable energy spread and fight to climate change.

Looking at some of the built examples presented in this chapter, in several cases significant elements of innovation — belonging to one or more of the above sub-classes — can be individuated. For instance, one can cite: the pilot application of the thermal/PV element

(SolarWall® BIPV/T) at the School of Business in Montreal, that helped the launch of this novel "hybrid" product; the innovative installation at Kollektivhuset of rather "conventional" semi-transparent crystalline silicon modules, with the sliding and colored rear panels and the possibility to extend easily the solar plants for each apartment[44]; the experimental façade of the Xeliox Energy Labs, with its novel energy and architectural concept, designed to maximize the energy production and to capture the attention of the public; the peculiar composition with "staggered" squares, made of standard crystalline modules, installed as elements of protection (from falls as well as from wind and sun) in the façade of the student housing building at the harbor of Aarhus; the sun-tracking and sun-shading element of the EWE Arena in Oldenburg, maximizing the building response to the stimuli from the external environment; the PV-activated lamellae of the Plus Energy House from 2007 Solar Decathlon, adapting to the sun-path in order to provide the building with a better energy performance.

In particular, looking at the last two examples cited, the theme of **sun-tracking dynamic façades**, following the solar path and maximizing the exploitation of its energy potential, turns out to be particularly fitted for PV applications and it indeed has been engaged with a great variety of innovative technical and design solutions, often with successful outcomes in architecture and energy terms.

In this field, for example, the so-called "Soft House" (Photo 29) stands out for its utmost innovative design regarding both module installation as well as the overall concept of the building. This plus-energy prototype building[45] by Kennedy & Violich Architecture[46] was presented in 2013 in the "Smart Material Houses" competition at the IBA Hamburg[47]. It is characterized by a multifunctional "dynamic structure", covering part of the roof and of the south-exposed façade. It is made of ribbon-like elements, able to bend (roof) or twist (façade) in order to capture the sun, conferring to the building a peculiar ever-changing architectural expression as well as an optimized energy performance.

This unique moveable roof-façade structure consists of two main portions:

- on top of the building, flexible fiberglass-reinforced plastic (GRP) boards, with thin-film solar modules installed, are able to bend and tilt according to angles that vary based on the weather conditions in order to follow the sun just like a sunflower and to maximize the energy output[48]. In winter, the angle of tilt increases, in summer it gets closer to the horizontal (0°), whereas in case of storms it is equal to 0°.
- on the façade, the strips overhang the edge of the roof and are substituted by so-called "twisters", which consist of flexible and 35%-translucent PTFE membranes, able to twist, indeed, in order to respond to sunlight variations during the day and to allow for optimal thermal and visual comfort conditions inside the apartments. The upper part of these façade elements are integrated with PV too.

The thin-film CIGS modules (6000x500x3mm) on stainless steel substrate[49] are fixed mechanically to their supporting structure: in particular, they are clamped at the upper end and mounted along the rest of their length by welded brackets[50]. Apparently, for the sake of minimal use of materials, the intention of the building planners was to utilize a multifunctional

BIPV solution, able to substitute integrally the roof/façade membrane, and not "just" a standard flexible thin-film module mounted onto it as an additional layer for electricity production. However, for technical and economical issues, they had to opt for a standardized building-added solution[51].

The "Soft House" roof-façade membrane structure is supported by a steel pipe construction that is anchored to the flat roof and the ground, integrating also the motors and hydraulic conduits for the activation of the twisters. This project required several tests on the materials of the membrane — due to the novelty in their use — and special wind tunnel tests turned out to be necessary to assess the mechanical performance of the structure. Besides this peculiar, moveable and multifunctional sun-shading, daylighting and PV element, the building is provided with a series of intelligent and sustainable solutions, that helped to reach a very efficient energy performance: the calculated Energy Use Intensity (EUI)[52] is indeed 67 kWh/m^{2}year and the photovoltaic production reaches 24,000 kWh/year. The surplus energy is injected into the local grid and sold, generating economic revenue.

Overall, «...*the innovation of this system lies in the way in which it brings together shading, energy production, and daylight...*»[53] by means of a stand-out architectural element that is able to maximize the energy efficiency of the building, while valorizing in a completely new and peculiar way its appearance.

It should also be noted that the "Soft House" exhibits an innovative, effective and architecturally satisfactory way to integrate standard thin-film modules on flexible stainless steel sheet into a building and it exploits their lightness and capability to be bent and twisted in order to intelligently track the sunlight and maximize both their passive and active energy performance. Such products — mostly used in buildings in limited roof-top integrated applications — represent an alternative to flat and rigid silicon panels and can provide totally different architectural and constructional performance, which can be creatively explored by architects: this building represent an emblematic example and reference in this sense.

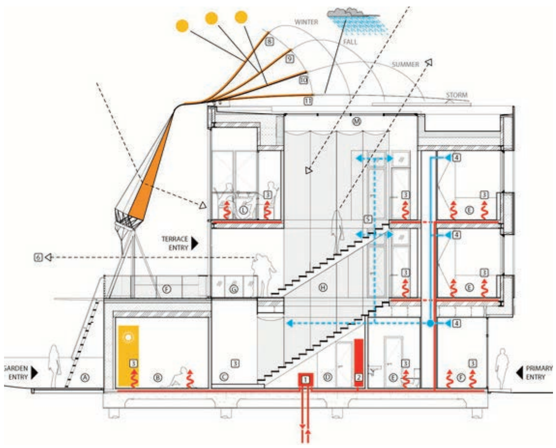


Photo 29 - The "Soft House", kvarch, Hamburg, 2013
Figure 3.9 - Cross section illustrating how the PV membrane responds to different climatic conditions as well as HVAC systems (e.g. geothermal pump)

Speaking of innovation, it is important to note how photovoltaics used as construction material and as element of the architectural project, thanks to its manifestly smart and green nature, nowadays represents, for the public and for the building designers themselves, a symbol of the technological progress and an "icon" of sustainability (Scognamiglio, 2010). In this sense, for example, PV technology becomes the ideal partner to be combined with novel technologies (such as LED lighting) for the creation of **digital and multimedial surfaces** able to convey images and messages, in an energy-efficient way.

For example, it is worth to mention the Green Pix Zero Energy Media Energy Wall (Photo 30) in Beijing (2008) by Simone Giostra and Partners[54], with the support of Arup, which undertook the aspects concerning both the lighting and the façade technology. This glazed curtain-wall installed on the south façade of the Xicui Entertainment Complex is one of the biggest colored LED screen in the world (about 1,800 m^2) and it is completely self-powered — zero-energy, indeed — thanks to the integrated photovoltaic system, generating during the day twice the energy needed during the night by the façade[55], on whose surface colored and animated projections come alive.

With the R&D support of leading German manufacturers Schüco International and Sunways, Giostra and Arup developed a new technology for laminating solar cells in a glass curtain-wall and oversaw the production of the first glass solar panels by Chinese manufacturer SunTech[56]. In total, 3,000 pc-Si wafers were used; wafers are laminated onto translucent glass substrate forming square-shaped (800x800 mm) panels and distributed with varying "density" along the building skin, letting natural light in, while reducing heat gain. The panels are installed vertically by means of spider clamp fixings to the steel structure of the façade and some of them are slightly tilted along their vertical axis, so that the façade obtains an irregular and corrugated surface. PV panels are integrated as finishing elements of the façade system and each also represents a "pixel" of this innovative low-resolution screen. A fluorescent lighting element is disposed behind each of the translucent façade panels, rear-illuminating it for the artistic projections that are controlled by means of sensors, placed inside the building. A catwalk, placed between the supporting structure of the façade and the internal wall of the building, allows for an easy maintenance of the screen.

Besides the innovative concept — which has been defined as "groundbreaking" and "unique" — also module design and installation systems have been specifically developed and optimized for the attainment of such intelligent building skin, which successfully integrates architecture with sustainable and digital technologies and, as the designer Giostra underlined, «...*represents a great advancement for the solar energy industry in China...*»[57].

Another emblematic example of multimedia PV-integrated surface is the urban installation called "Greeting to the Sun" in Zadar, Croatia (Photo 31). It was built in the field of a complete renovation of Zadar seashore, very close to city's historical center, after the completion of another urban installation: the "Sea Organs", a stone staircase right at the edge of the seafront that, thanks to a particular engineered system of underwater plastic pipe tubes, is able to produce ever-changing melodies and sounds at the passage of waves.

The same principle of "playing" with natural resources to generate a unique experience for the people walking in the Zadar peninsula seashore inspired the "Greeting to the Sun", a solar-powered and walkable screen for artistic projections. This artistic PV installation is a circle with a diameter of 22 m, finished with approximately 300 walkable PV panels, installed at the same level as the stone paving of the area. During the day, the solar panels convert sunlight into electricity[58] that is stored and later used for activate artistic digital projections (and, as for the surplus, utilized to power the lighting elements of the renovated seashore). At sunset, this PV-integrated surface comes alive thanks to a set of about 10,000 bulbs lights, which are installed below the panels and radiate light in varying colors and intensity, conveying images and messages. Users are able to walk on this luminous surface and interact with it, «*...feeling as if walking through an immaterial environment or swimming in water or as if the sole was moving under the feet...*» (Rossetti, 2011, p. 4). This energy self-sustaining urban art installation shows an original and completely new way to integrate respectfully and attractively solar energy within a historical context. The "Greeting to the Sun", along with the "Sea Organs", helped transforming this site, right at the edge of the old town and formerly rather unfrequented, into one of the most crowded spots of the city, successfully reaching the main purpose it was built for: valorizing through architecture Zadar peninsula, increasing the value of the city, and supporting the relaunch of tourism in that area.

Green Pix Zero Media Energy Wall by Simone Giostra and the Greeting to the Sun by Nikola Bašić are two of the most successful examples of this type of solutions, where digital and multimedia surfaces have been made totally or partially energy self-sufficient, thanks to the PV integration. It is of relevance to note that in none of these cases PV was concealed; rather it has been made visible in order to express its smart and sustainable values[59].

A similar approach regarding **PV-activated luminous façades** can be found in "Valbygavlen" (Photo 32), a work of art based on the project by the Danish artist Anita Jørgensen and added to the existing façade of the Cultural and Sports Centre in Valby, a marginal development area in the city of Copenhagen.

Photo 30 - Green Pix Zero Energy Media Wall, Beijing, 2008

Photo 31 - The Greeting to the Sun, Nikola Bašić, Zadar, 2008

Photo 32 - Valbygavlen, Anita Jørgensen, Copenhagen, 2008

This building-added system was realized in 2008 in the field of a PV implementation plan in the Valby district[60] and it was commissioned to fulfill the important role to become a recognizable symbol of it, inspiring to use solar panels in different ways[61]. And it is not a coincidence that the building surface chosen for this installation is next to a railway and therefore visible to thousands of people travelling in and out of Copenhagen everyday, just like a gate to the city[62]. "Valbygavlen" is characterized by an irregular pattern of homogeneous black PV panels, rectangular in shape. Standard thin-film panels in different dimensions are arranged in different positions on the façade and the horizontal joints between panels are thicker and thus result more evident than the vertical ones. Red neon tubes are installed according to a peculiar design and glow in the night, giving life to the artistic installation (that, differently than the two above-described examples, is static).

Some have criticized the "unfinished" day-time look of the system, which functions as an artistic installation only in the night (Andersen, 2011). During the day, de facto, the supporting structure of the system becomes visible and the neon tubes, although turned-off, are perfectly distinguishable; however, the irregular black surface of the PV panels still stands out with its varying appearance due to the sky's reflections, fulfilling its role as landmark also during daytime. In the aforementioned projects in Beijing and in Zadar, PV modules — specifically developed for those installation — are integrated functionally as finishing and/or cladding elements of the involved surfaces. Differently, in this case the solar system, involving standard modules and mounting systems, is simply added to the existing façade without fulfilling any technical role than the night-time illumination performance.

The Swiss Pavilion at 2010 Expo in Shanghai, by Buchner Bründler, revisits the theme of PV-activated luminous surfaces through an even more innovative approach: the PV units become round, red, tiny plates, integrated with a small polycrystalline silicon solar device and suspended on a semi-transparent metallic net surrounding the whole building like a curtain. These small elements (about 10,000, sold as souvenirs after the exhibition) consist of a circuit board with electronics depicting the map of Switzerland and a transparent red polycarbonate casing, with a solar cell integrated. Each element stores the energy collected from the sun and, thanks to integrated LEDs, can sparkle, like little red pailettes, as a response to external stimuli coming from the sun and the flashing lights of visitors' cameras or either, in the night, as a result of the reciprocal triggering of the elements. This particular solution «...*playfully demonstrates how much - yet unused - energy is surrounding us. At the same time, it demonstrates how technology, energy and architecture could gainfully be linked...*»[63].

Another recurring aspect, which has led to innovative design concepts, has exploited the modularity of PV systems that come from the assembly of units of varying dimensions — cell, module, panels, strings — for the attainment of **patterned and "pixelated" surfaces**[64].

With "pixelation" is meant a graphic process — which has its roots in the "Pointillisme" of the XIX century and is at the basis of the functioning of digital screens — where a basic, simple unit, the pixel indeed, is utilized to compose more or less complex images that from afar can be perceived as more or less defined based on the dimension and density of the pixels.

Pixelation has been diffusely used in contemporary architecture, as organizational and pattern generating principle of architectural surfaces (Baum & Liotta, 2011)[65].

This process starts with the digital acquisition of the images to be reproduced and with their enlargement until a low-resolution picture, made of clearly distinguishable pixels, is generated; finally, the texture of pixels is physically transformed into an architectural surface by means of different possible techniques[66]. For example, in the Vinorama building in Rivaz (Switzerland), designed by Atelier Daniel Schlaepfer, a "pixelated" façade helped solve the delicate issue of the respectful and coherent integration in a landscape recognized as World Heritage by UNESCO. In particular, the façades of the building present a golden-green steel canvas representing grape vines and leaves in a pixelated stylization, allowing for a coherent integration of the building within its natural landscape, both at the visual and conceptual level (given the function of the building, dedicated to the promotion of vineyards and wine). In this field, great potentialities can be acknowledged to PV and, in particular, to first-generation technologies, based on a small, either square or round unit that can be easily associated physically and conceptually to a pixel: the crystalline silicon "wafer". Baum & Liotta (2011), for example, considered this as an inherent quality of first-generation technologies, especially as regards light-transmissive solutions. In this regard, it is worth to mention renovation of a 1920s electric substation of the EDF in Paris, by Emmaneul Saadi. The transparent surfaces of this "incubator" of innovative companies (also known as Hotel Industriel "Le Losserand") were covered in semi-transparent PV laminates with silicon wafers disposed according to an apparently random pattern, generated from the pixelation of the image of the natural stone cladding the building (Photo 34). Interplays of light and shadow occur during day and night as a result of the light crossing the irregular pattern of the PV surfaces. The same approach might be used, at a bigger scale, for the arrangement of modules according to specific patterns: this is the case, e.g., of the "Platine" at Saint Etienne Cité du Design[67], where the pixelation of the daylight distribution on the top envelope of the building generated the rule for the distribution of the ten different types of triangular infill elements, among which two different PV module technologies — c-Si and DSC — were included (Photo 35).

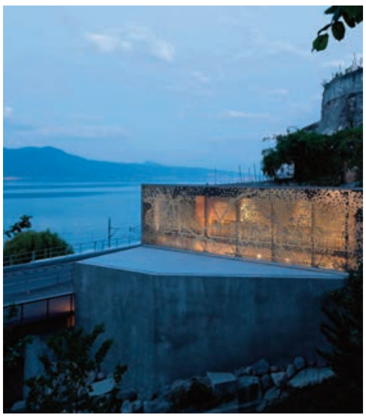


Photo 33 - Vinorama, Atelier D. Schlaepfer, Rivaz, 2010: view of the organic-inspired pixelated façade

Photo 34 - Le Losserand, Paris, Emmanuel Saadi, 2013: pixelation generative process explained

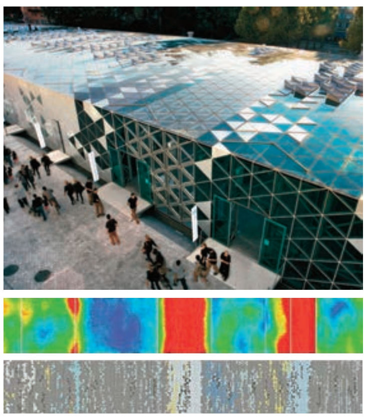


Photo 35 - Cité du Design, Saint Etienne, LIN Architects, 2008: pixelation generative process explained

Speaking of innovative BIPV designs involving pixelated and patterned surfaces, Baum & Liotta (2011) also investigated the possibility to apply *«...the inventory of local cultural heritage as an inspiration for technological innovation...»* by using traditional motifs of Japanese family crests (kamon) as pattern generating elements for semi-transparent PV laminates. Through the combination of different patterns of solar cells and prints on the inner glass layer of the PV laminate, the authors reinterpretate through modern technologies traditional icons of Japanese culture: beyond the aesthetic result (Figure 3.10), this work is of relevance for having underlined how culturally inspired referencing for the design of innovative BIPV devices can also contribute to their public acceptance.

A similar approach was pursued by E2A Architecture in the extension of Menara Marrakesh Airport, designed with the aim to combine modern technologies and materials with elements of Moroccan tradition (Photo 36). The steel structure of the terminal roof sustains 72 pyramidal skylights integrating on two faces semi-transparent crystalline silicon modules. Wafers are arranged according to a geometrical pattern that recalls traditional motifs of islamic architecture that is also reprised in the perforated elements that ornate the building façades. In this way, interesting light effects are allowed, in a contemporary reinterpretation of traditional elements of islamic architecture, i.e. the *masharabiya*.

Besides wafer-based technologies, the modularity that is intrinsic of photovoltaic technology, has also been interestingly exploited to generate innovative and sustainable design concepts for the building envelope. For example, in the reorganization of ThyssenKrupp Steel facilities in Duisburg-Beeckerwerth (Photo 37), a unique-looking BIPV façade was obtained from the composition of custom-made green steel elements integrated with blue triple-junction solar modules[68]. The colours of the façade, chosen in collaboration with the Friedrich Ernst von Garnier color design studio, and the wave-like distribution of the PV modules on the façade help the façade blend in the surrounding landscape, conferring to this renovated industrial building an attractive overall appearance, in contrast with the "cold" look commonly expected from manufacturing plants.

Figure 3.10 - PV elements inspired by Japanese tradition (Baum & Liotta, 2011)

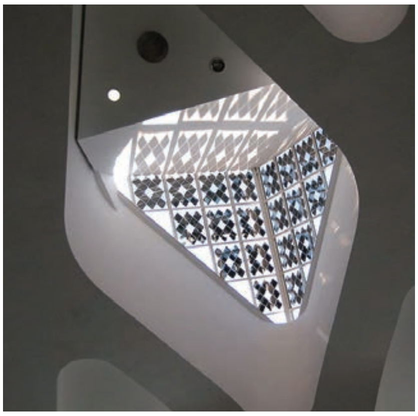


Photo 36 - Menara Airport, Marrakesh, E2A architecture, 2008: Masharabiya-inspired skylight

Photo 37 - ThyssenKrupp Steel Building, Duisburg, Cerny Gunia, 2002: PV-integrated blue and green façade

From the overview provided in the previous pages, it is evident how an innovative design approach, regarding both solar modules and their installation systems as well as concerning the concept behind the building design, can be a driving force for the achievement of positive results in terms of architectural, constructional, and energy performance and "quality" of the PV integration.

3.5. Case Studies

The "criteria" proposed for the evaluation of the integration level of PV in buildings were the result of the thorough analysis of literature (which has been widely discussed previously in this chapter), but also, most importantly, came out from an in-depth study of built examples of PV use in buildings, starting from the individuation of some of the key-features for the "success" of the examples analyzed.

The first step, in this study, was the collection of a large number of these examples of PV use in buildings, where it has been possible to individuate interesting solutions for the integration of PV technology.

Several case studies, referring to both new and retrofitted buildings mainly of the last two decades, have been found: in literature; in dedicated publications on BIPV and NZEBs; in online databases, often elaborated in the field of European Projects[69]; in the reference section of the websites of BIPV and PV companies. In particular, a preliminary list of over 100 examples has been elaborated[70]. This list collects, breaks down, organizes, and relates the acquired information on each of the case study, taking into account general building data as well as more technical information regarding the used PV technologies and products, as well as the characteristics of the PV installation. This way it has been possible to acquire a wide picture of the architectural integration of photovoltaics both at product/technology and concept level. Given the large number of projects analyzed, this study also enabled to make some of the considerations about individuated trends and possible developments that have been widely discussed in the previous pages.

In order to present in a synthetic and comprehensive way most relevant information, case-study sheets have been elaborated for 27 of the catalogued built examples, which have been selected on the basis of one or more of the following criteria:

- the presence of interesting features, useful to illustrate some relevant information regarding the use of PV and/or BIPV technology in the architectural projects;
- the absence, in literature, of an organic and detailed analysis of the building and of its PV system, from both architecture- and PV-related points of view;
- the recourse to a novel product or technology or to a particular strategy for the design.

Moreover, it has been tried to avoid the repetition of similar solutions.

The case-study sheets are structured and conceived to allow for an easy comparison of the case studies among each other and for an immediate individuation of main information. Furthermore, in each sheet, the architectural integration is assessed according to the above-introduced criteria.

The catalogued examples have been divided into two main categories: new construction, *n* (pp. 147-168) and retrofit/renovation, *r* (pp. 169-183), also corresponding to two different colors of the case-study sheets (respectively, green and grey).

The typical structure of a sheet is divided into two parts:

- the first part contains general building data;
- the second part regards the characteristics of the PV installation/s and can be extended when more than one PV installation occur in the examined case study.

The first part is useful for a quick overview of the characteristics of the case study building and of the PV installation. It provides general information about each case study (name of the building, design team, significant dates, geographical location, context[71], climatic data, building type) and is provided with a brief general description of the building, which focuses on energy- and PV-related aspects.

In order to give some synthetic information about the climate data for each building, in particular, two main parameters were given.

The first one regards the climate zone that analyzed building belongs to, classified according to Köppen-Geiger climate classification[72], ranging from equatorial (A), arid (B), C temperate (C), snow (D), polar (E). The indication of the climate zone is useful to provide synthetical information about type of climate, precipitations, and temperatures and to be able to make a brief comparison between different building sites[73].

The second climatic parameter was given to provide some information referring to the solar potential of location of analyzed building: this is the Global Horizontal Irradiation (GHI) that is «*…the most important parameter for evaluation of solar energy potential of a particular region and the most basic value for PV simulations…*»[74].

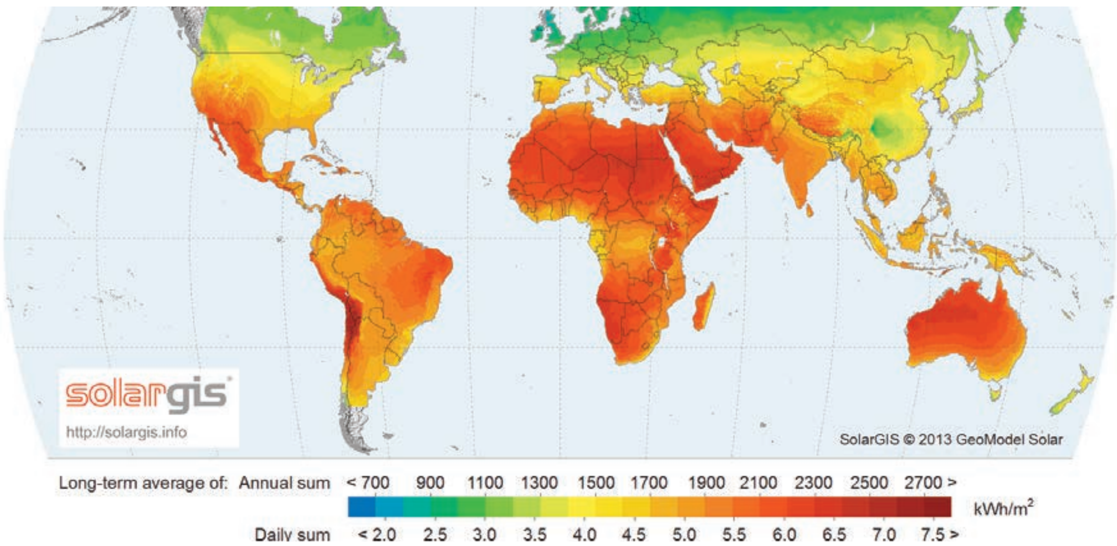


Figure 3.11 - World map illustrating the distribution of Global Horizontal Irradiation GHI (solargis.info)

More in detail, GHI (expressed in KWh/m^2) is the irradiation that reaches a horizontal Earth surface in the given site. It is the sum of two quantities: the Direct Horizontal Irradiation (DHI), which is the irradiation component that reaches a horizontal Earth surface without any atmospheric losses due to scattering or absorption, and the Diffuse Horizontal Irradiation (DIF), which is the irradiation component that reaches a horizontal Earth surface as a result of being scattered by air molecules, aerosol particles, cloud particles or other particles. In the absence of an atmosphere there would be no diffuse horizontal irradiation[75].

A list of icons allows for an immediate individuation of some important information that are analyzed in detail in the second part of the sheet. In particular, for each photovoltaic installation, three different icons are provided: the first one is used to indicate whether we are dealing with a building-integrated or building-added application, underlining whether the PV system is a multifunctional device coinciding with one or more functional layers and/or elements of the building fabric or simply is added on top of the already finished building skin; the second of the three icons allows for an immediate individuation of the photovoltaic technology/generation used in the analyzed application; the third one, instead, illustrates graphically the components partially or completely substituted by the multifunctional building and PV product or, in case of BAPV systems, the components to which the PV module is added.

The icons are reported and explained in Tables 3.4-3.7. They are organized in columns, each corresponding to the different PV installations occurring in the building.

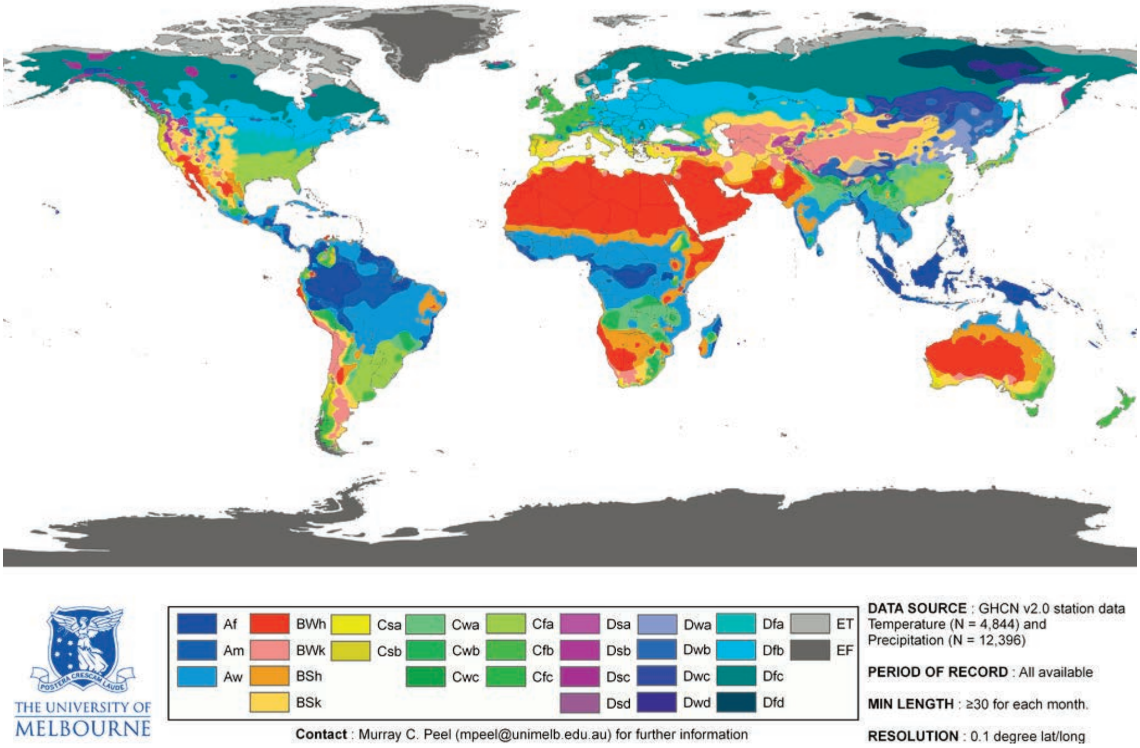
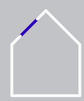
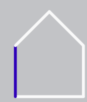
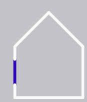
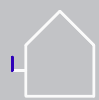
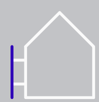
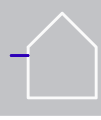
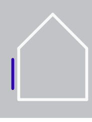


Figure 3.12 - World map of Koppen-Geigen Classification (Peel et al., 2007)

TYPE OF INSTALLATION		
	Description	Icon
Building Integrated Photovoltaics	PV modules integrated into the envelope constructive system. Modules coincide with technical elements and/or functional layers of the building system	BI PV
Building Added Photovoltaics	PV modules applied on top of the building skin. Modules are simply added to the already completed building envelope	BA PV

BUILDING INTEGRATED PHOTOVOLTAICS			
Sub-system	Example of assemblies or components		Icon
External Envelope	Top Envelope	Roof	
		Roof-light	
	Side Envelope	Façade	
		Window	
Spatial Divider outside the Envelope	External Vertical Divider	Parapet	
		Partition wall	
	External Horizontal Divider	Canopy	

BUILDING ADDED PHOTOVOLTAICS		
Component		Icon
Roof	Stand-off system on roof	
Façade	Stand-off system on façade	

PHOTOVOLTAIC TECHNOLOGY		
Generation	Technology	Icon
1st Generation	Mono-crystalline silicon	mc -Si 1
	Poly-crystalline silicon	pc -Si 1
2nd Generation	Amorphous silicon	a -Si 2
	Micromorphous silicon	μm -Si 2
	Cadmium Telluride	Cd Te 2
	Copper Indium Gallium Diselenide	CI GS 2
	Copper Indium Diselenide	CIS 2
3rd Generation	Dye-sensitized Solar Cells	DS SC 3
	Organic Photovoltaics	O PV 3

Table 3.4 *(left page, top)* - Assemblies or components (ISO 6241) where BIPV is integrated and related icons
Table 3.5 *(left page, center)* - Assemblies or components to which the PV module is added and related icons
Table 3.6 *(left page, bottom)* - Definitions of BIPV and BAPV and related icons
Table 3.7 *(top)* - Different PV technologies and generations plus related icons

The second part of the case-study sheets examines in detail the PV system/s, by providing specific information on characteristics and performance of PV product and its installation. In order to identify in detail the used (BI)PV product, the information provided — when available — regard product's commercial name, related PV technology, cell and module manufacturers, dimensional characteristics, and other relevant specifications (substrate material and characteristics, stratification of the modules, presence/absence of the frame and related characteristics, etc.).

Another important indication refers to whether modules are standard or custom-made elements.

As regards the PV installation, in the case of building-integrated application, the sub-system and component as well as functional layer and/or element[76] involved in the integration individuate clearly the additional building functions provided by the module (besides, of course, the electricity production). In case of building-added installations, the sub-system and component are indicated in order to show where in the building the installation occurs, but no added functions are individuated.

In the case of retrofit, when referring to the PV installation, it has been considered of relevance to underline whether the analyzed PV system is added or integrated on the surfaces of the existing building or rather on newly-added volumes[77]. Indeed, these two options, which could be linked to a very wide variety of reasons (concerning heritage protection, technical and economical considerations, and so on) certainly lead to radically different results and possibilities.

The other information regarding the installation (fixedness/movability of the modules, orientation, total PV surface, and other eventual specifications) and its performance (power installed, yearly production, yearly production per power installed i.e. kWh/kWp year) allow for a comparison of the different examples and for a deep characterization of the plant of the analyzed case-study building. In the buildings where two or more PV installations occur, the second part of the case study sheets can be extended, by repeating it as many times as the number of ways PV is installed in the building.

This part of the case-study sheets also presents a check-list containing a list of features that are considered relevant for an evaluation of the example of PV use in the analyzed building and of its "integration level". In fact, this work aims to provide some instruments and outline some features that can be useful to make some considerations on the architectural "integration level" of the catalogued examples of PV use in buildings.

The four different integration criteria proposed and widely discussed previously in this chapter (cf. paragraph 3.5), in particular, refer to:

A. The **Design strategy** that has led the project of each installation and has been relevant to define its expressive-morphological role of the PV system into the overall architectural concept of the building.

It is further divided in five sub-classes (individuated by Weller et al. 2010):

- *subjugation*: it applies to those installations that are placed on or in front of a building without any architectural goals and whose sole task is to produce electricity;
- *domination*: it applies to those cases when the solar technology has a decisive effect on the design of a new building, i.e. its orientation with respect to the sun, its volume and the configuration of the building envelope;
- *integration*: it applies to those cases when the solar technology and the building structure are equal partners in a symbiotic system;

- *subordination*: it applies to those installations where the PV system is hardly apparent because of its shape and size, its position with respect to the observer and public spaces, or its colour, thus playing a subordinate role;
- *imitation*: it applies to those installations where the PV system is designed to copy traditional forms of construction, replace their functions and, at the same time, add an active solar layer.

B. The **Multi-functionality** of the studied PV installation, taking into account the technical-functional role of the PV system in the building fabric as well as the potential role PV plays for the definition of building appearance, besides that related to the electricity production. It is further divided into two sub-classes:
- *Multi-functional building and PV element*: in case PV modules are removed, the original function of the technical element/functional layer is no longer met and the substitution of the PV with adequate technical elements/functional layer is therefore needed;
- *PV with relevant aesthetic role*: PV module is an active part in building image definition; this means materials are visible and the aesthetic potential of the PV technology is explored.

C. The **Other Bioclimatic Functions** of the considered PV installation, focusing on the potential energy-saving relapses related to the use of the PV system, besides those related to its electricity production and efficiency. It has been divided into sub-classes too:
- *Solar and thermal protection*: this sub-class refers to the possibility to optimize/control/regulate the exchange of solar and thermal energy across the envelope through the correct design of the PV installation (e.g. daylight control provided by PV modules installed as either fixed or movable louvers and brise-soleil; sunshading provided by semi-transparent PV modules integrated onto transparent and/or translucent elements of the building envelope; and so on…);
- *Passive exploitation of conversion heat*: this sub-class refers to the possibility to exploit the conversion heat that is developed on the rear of the modules in order to activate passive mechanisms of ventilation and/or heating.

D. The **Elements of Innovation** of the analyzed PV installation, referring to the novelty of:
- *Module Design*: the novelty regards module design and, for example, it can involve color treatment, finishing, pattern and/texture;
- *Module Installation*: the novelty lies in the way modules are installed and, for example, it can involve the technological as well as aesthetic characteristics of the elements used for the integration (jointing/fixing systems, support structure, etc.);
- *Integration Concept*: the novelty regards the overall integration concept, which can even involve “standardized” and/or “traditional” modules, and it lies in the relapses that the PV installation has on overall building energy performance as well as on the level of building image.

The case-study sheets that are reported in the following pages provide a wide overview of the contemporary scenario as regards the use of PV technology in buildings: 27 buildings are analyzed and 38 different installations are evaluated (24 and 14 respectively of new constructions and retrofit/renovations).

The main target of this case-study analysis are building planners (architects and engineers): the organized collection of information, provided through the case-study sheets and related to existing successful examples of architecturally integrated PV, could not only provide more tools to understand what an architectural integration is, but also help a more conscious use of PV in buildings. Moreover, although this study has not the intention nor the characteristics to provide statystical information, it allows outlining some further aspects of interest, in addition to what already widely discussed in this chapter.

Out of the large number of analyzed installations, only 6 are building-added (less than 1 out of 6); half of these 6 are stand-off PV systems placed on the building roof without a relevant aesthetic role and, unless of peculiar cases (see Bahaus Building, r07), complementing other systems installed more “visibly” in the façades (see for example n04, n09). This figure bears witness to the variety of architecturally relevant solutions that can offer an alternative to the most spread and conventional roof-mounted PV added systems. In addition, it is of relevance to note that this wide variety of solutions reported relies for the main part (31 out of 38 of the analyzed installations) on first-generation crystalline silicon devices, whereas only 6 case studies have second-generation thin-film modules installed and only 1 is characterized by the integration of third-generation PV elements.

The majority of the analyzed examples (24) are located in Europe (especially Central and Northern Europe), one is in the US, one in China, and one, instead, is an itinerant prototype building. If we also consider that the only two buildings located outside Europe are from Italian Architectural firms (i.e. Renzo Piano Building Workshop, Mario Cucinella Architects), it is possible to conclude that Europe is certainly a front-runner in the field of the architectural integration of photovoltaics, both in terms of architectural projects and on the product side. Indeed, out of the big number of manufacturers of both solar cells and BIPV/PV components that can be encountered in the following pages, most are European (or Europe-based) companies. This could be also linked to the fact that often local manufacturers are chosen for a more direct involvment in the projects: for example, out of the 8 Danish case studies, 6 have been supplied as for both the PV cells and components by Danish manufacturers. Such close involvement indeed might be needed due to the fact that most of the PV components installed are custom-made, often specifically developed for a given project, and their production is bespoke. Among the BIPV manufacturers, it is possible to list: glazing, window and façade manufacturers that either partner with solar cells producers or have a specific branch in the BIPV sector (e.g. Schüco, i.e. the most recurring company in the case-study sheets, Pilkington, Saint Gobain Glass Solar, Schott Solar, Scheuten Solar, Ertex Solar); and PV companies that often develop specific product lines dedicated to the BIPV or rather are called to solve the specific problems of a given project (e.g. Gaia Solar, Sharp).

case studies **NEW CONSTRUCTION**

n01	*California Academy of Sciences*, RPBW & Stantec Architecture, San Francisco (US)	2008
n02	*Solcellegarden,* Arkitema Architects & Ole Dreyer, Aarhus (Denmark)	2002
n03	*SIEEB*, Mario Cucinella Architects, Beijing (China)	2008
n04	*Plus-Energy House for Solar Decathlon*, Darmstadt Technical University, Itinerant	2007
n05	*Cité du Design*, LIN Architects, Saint Etienne (France)	2008
n06	*Swiss Tech Convention Centre*, Dahl Rocha & Associates, Lausanne (Switzerland)	2014
n07	*Novartis "Fabrikstrasse 15" Building,* Gehry Partners LLP, Basel (Switzerland)	2009
n08	*Oslo Opera House*, Snøhetta A/S, Oslo (Norway)	2007
n09	*Energimidt*, Aarstiderne Arkitekter, Silkeborg (Denmark)	2009
n10	*Soft House*, Kennedy & Violich Architecture, Hamburg (Germany)	2013
n11	*Lehrter Station*, gmp architekten, Berlin (Germany)	2002
n12	*Power Tower - Energie AG Headquarters*, Weber & Hofer, Linz (Austria)	2008
n13	*Low Energy Aarhus Municipality Office Building*, CF Møller, Aarhus (Denmark)	2010
n14	*Social Housing in Quay de Valmy*, Emmanuel Saadi & Jean-Louis Rey, Paris (France)	2011
n15	*The House of Music*, Coop Himmelb(l)au, Aalborg (Denmark)	2014
n16	*Crowne Plaza Copenhagen Towers*, Dissing+Weitling, Copenhagen (Denmark)	2009

n01

California Academy of Sciences

Renzo Piano Building Workshop, Stantec Architecture
San Francisco, US

The California Academy of Sciences really is a showcase of sustainable design strategies. It wastes 1/3 less energy than comparable structures and 10% of its energy demand is self-generated thanks to a glass and steel "Solar Canopy", producing electricity while tuning the sunlight striking building façades thanks to custom design. The idea of integrating PV modules came in a second moment and represented a big challenge in the design process as well as a key factor for the achievement of LEED Double Platinum certification. The "Solar Canopy" avoids the emission of 184 t of CO_2 every year and, along with the "Living Roof", became the symbol of this Museum of Sustainability, visited by thousands of people every year.

Building Facts

Year of completion: 2008
Context: Historical Park
Building type: Museum
Energy consultant: Arup
Climate: Dry summer subtropical, Csb
GHI: 1900 kWh/m^{2}year

Specification on PV system

PV Product	SolarSave® Architectural PV Glass
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Applied Solar, Inc. (ex Open Energy Co.)
Module Manufacturer	Suntech Power Holding (installed by PermaSteelisa)
Number, Dimensions	720 modules (55,000 cells), 1.22x1.83 m
Standard/Custom-made	Custom-made
Specifications	Frameless PV modules on glass substrate coupled with half screen-printed glass with white cell-like squares

PV Installation	Building Integrated
Sub-system	External horizontal divider
Assembly or component	Canopy
Functional layer/element	Sunlight attenuation element
Additional info	Cell-like squares were designed with different patterns and dimensions to provide right shading/daylight levels
Fixed/Movable	Fixed
Orientation	0°
Surface	1,600 m^2
Power installed	n.g.
Yearly production	213,000 kWh/year (10% of electricity need)
KWh/kWp year	n.g.

Integration Criteria

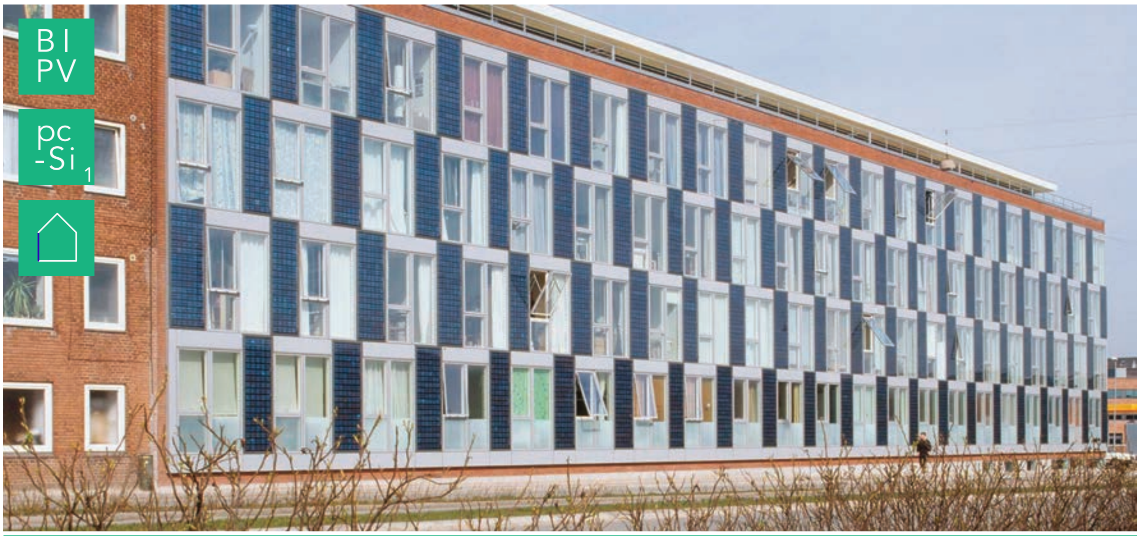
Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	■
Integration concept	

Marco Morini



n02

Solcellegården

Arkitema Architects, Ole Dreyer
Aarhus, Denmark

Solcellegården (i.e. "solar farm") is a student accommodation building, located not far from Aarhus city center. Its south façade is characterised by 84 multifunctional PV-integrated components, developed in close co-operation between the architect, window manufacturer and solar installer. The components consist in two pieces: a "dark" element corresponding essentially to a PV-integrated "solar wall" that acts as insulating cladding, power producer and air pre-heater and a "transparent" part consisting of an openable element with a parapet. The fixing system was developed to ensure quick and secure mounting as well as maintenance. The PV system has a determining influence on the architectural result.

Building Facts

Year of completion:
2002
Context:
Central city
Building Type:
Residential Building
Energy Consultant:
Niras A/S; oi-electrics
Climate:
Maritime Temperate, Cfb
GHI:
900-1000 kWh/m²year

Specification on PV system

PV Product

PV Technology	Polycrystalline Silicon
Cell Manufacturer	oi-electric
Module Manufacturer	oi-electric (aluminium framing by VELFAC)
Number, Dimensions	84 modules (125x125mm cells)
Standard/Custom-made	Custom-made
Specifications	The cavity between the solar panel and the interior cladding contains absorber, insulation and vapor barrier

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding element
Additional info	Solar wall system: air in the cavity rear the panels is pre-heated by the sun and can be exchanged with indoor spaces through air intakes near the ceiling
Fixed/Movable	Fixed
Orientation	90°, south
Surface	134 m²
Power installed	15.8 kW
Yearly production	8,200 kWh/year, measured (27% of building consumption)
KWh/kWp year	519

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	
Exploitation of conversion heat	■

Elements of innovation

Module design	
Module installation	■
Integration concept	■

n03

SIEEB

Mario Cucinella Architects
Beijing, China

The Sino-Italian Ecological and Energy Efficient Building (SIEEB) was built to to demonstrate the possibilities of sustainable and energy-efficient construction in China. In contrast to the compact north façade, the south side of the building is open and characterized by two wings with more or less adjecting terraces, shaded by a system of 190 PV panels, supported by a cantilevering steel structure. This system is a fundamental element of the energy and architectural concepts of the building, also contributing to define its form. The two wings maximise the solar gain on south side and create an internal vegetated patio, useful for building microclimate mitigation along with all other sustainable strategies.

Building Facts

Year of completion:
2006
Context:
Central city
Building Type:
Office Building
Energy Consultant:
Milan Polytechnic, Favero & Milan Ingegneria
Climate:
Warm temperate, Cwa
GHI: 1500 kWh/m^{2}year

Specification on PV system

PV Product	
PV Technology	Polycrystalline Silicon
Cell Manufacturer	EniTecnologie
Module Manufacturer	EniTecnologie
Number, Dimensions	190 modules, the basic element is 1.90x0.79 m
Standard/Custom-made	Custom-made
Specifications	Shiny blue PV panels, framed through white aluminum hollow section (38x38x4 mm)

PV Installation	Building Integrated
Sub-system	External horizontal divider
Assembly or component	Canopy
Functional layer/element	Sun-shading element
Additional info	Support structure is made of steel hollow sections that are mechanically fixed to cantilevering steel channels
Fixed/Movable	Fixed
Orientation	35°, south
Surface	150 m^2
Power installed	19.95 kW
Yearly production	25,000 kWh/year (avoided 36.9 t CO_2/year)
KWh/kWp year	1,253

Integration Criteria

Design Strategy	
Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	
Integration concept	■

n04

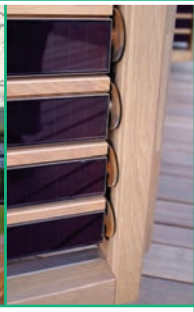
House for the Solar Decathlon

Darmstadt University of Technology
Itinerant project

This prototype of Plus Energy House was elected as winner of 2007 Solar Decathlon. The optimum energy efficiency of this house was obtained through a balance between passive measures for thermal insulation, natural cooling, solar gain and active systems. The southern side presents a buffer space that can be totally closed or opened according to the season by means of PV-activated lamellae installed onto foldable louvers. Such space is also provided with a semi-transparent glazed PV-integrated skylight, optimizing comfort inside the patio.
PV and solar thermal panels are installed in the roof, enabling this low-consuming house to produce more energy than needed.

Building Facts

Year of completion:
2007
Context:
-
Building Type:
Single-family house
Energy Consultant:
Darmstadt University of Technology
Climate:
-
GHI:
-



Specification on PV system

PV Product	ASI® OEM Outdoor Solar Modules
PV Technology	Amorphous Silicon
Cell Manufacturer	Schott AG
Module Manufacturer	Schott AG
Number, Dimensions	1,122 modules, 0.536x0.037 m
Standard/Custom-made	Custom-made
Specifications	Metal-embedded amorphous silicon glass plates, screwed onto wooden lamellae.

PV Installation	Building Integrated
Sub-system	External vertical divider
Assembly or component	Shutter
Functional layer/element	Sunlight attenuation element
Additional info	PV-activated lamellae, installed onto openable louvers of 3 house sides, tilt automatically following sunpath
Fixed/Movable	Movable
Orientation	Variable tilt (0°, 30°, 90°) and orientation (S, E, W)
Surface	approx. 24 m²
Power installed	2 kW (1.9 per louver)
Yearly production	11,300 kWh/year
KWh/kWp year	n.g.

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	
Subordination	■
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	■
Integration concept	■

Specification on PV system

PV Product	**Transparent Sunways Solar Modules**
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Sunways
Module Manufacturer	Sunways
Number, Dimensions	8 modules,1.55x1.15m (except for terminal ones)
Standard/Custom-made	Custom-made
Specifications	Frameless modules, made of 10% transparent hole-drilled cells and laminated into safety glass
PV Installation	**Building Integrated**
Sub-system	External horizontal divider
Assembly or component	Canopy
Functional layer/element	Sunlight attenuation element, infill element
Additional info	Glass panels with stainless steel spider holders, fixed to the timber structure of the building
Fixed/Movable	Fixed
Orientation	3° (tilted to north for water draining purposes)
Surface	approx. 11 m^2
Power installed	n.g.
Yearly production	n.g.
KWh/kWp year	n.g.

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	
Elements of innovation	
Module design	
Module installation	
Integration concept	

Specification on PV system

PV Product	**SunPower SPR-220 High Efficiency**
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Sun Power® Corporation
Module Manufacturer	Sun Power® Corporation
Number, Dimensions	47 panels, 1.56x0.80 m
Standard/Custom-made	Standard
Specifications	Anodized aluminium frame, high-transmission tempered front glass, high-efficiency cells with no gridlines
PV Installation	**Building Added**
Sub-system	Top envelope
Assembly or component	Roof
Functional layer/element	-
Additional info	Stand-off PV panels, slightly tilted to address rainwater to drains; one solar thermal panel is installed too
Fixed/Movable	Fixed
Orientation	3°, north and south
Surface	approximately 60 m^2
Power installed	9 kW
Yearly production	n.g.
KWh/kWp year	n.g.

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	
Subordination	■
Imitation	
Multifunctionality	
Multifunctional building/PV element	
PV with relevant aesthetic role	
Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	
Elements of innovation	
Module design	
Module installation	
Integration concept	

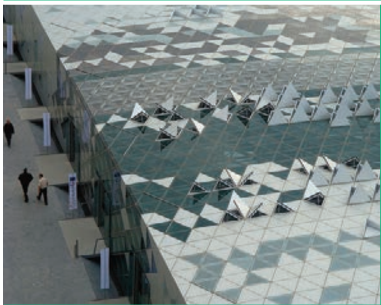
n05

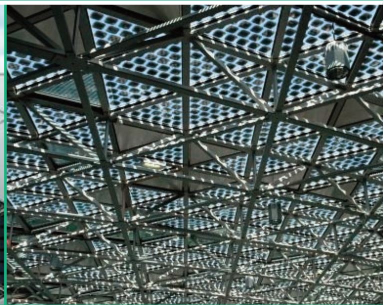
Cité du Design
LIN Architects (Fin Geipel + Giulia Andi)
Saint Etienne, France

The Cite du Design is an international design center and an institution for communication and research, built in occasion of the renovation of the area of the "Manufacture d'Armes", a former factory of munitions. The 7,000 m² new eco-friendly building (the "Platine") is the connection structure of the whole complex. The skin of the Platine is made of about 14,000 either fixed or openable equilateral triangles on three-dimensional structure of metallic profiles. Triangles made of different materials (different types of glass, metal, semi-transparent PV modules, experimental DSC panels) and disposed according to a pixellation process, help control light, temperature and air flow, according to building needs and activities.

Building Facts

Year of completion:
2008
Context:
Development Area
Building Type:
Multipurpose Building
Energy Consultant:
Matthias Schuler+Arnaud Billard, Transsolar
Climate:
Maritime Temperate, Cfb
GHI: 1250 kWh/m² year



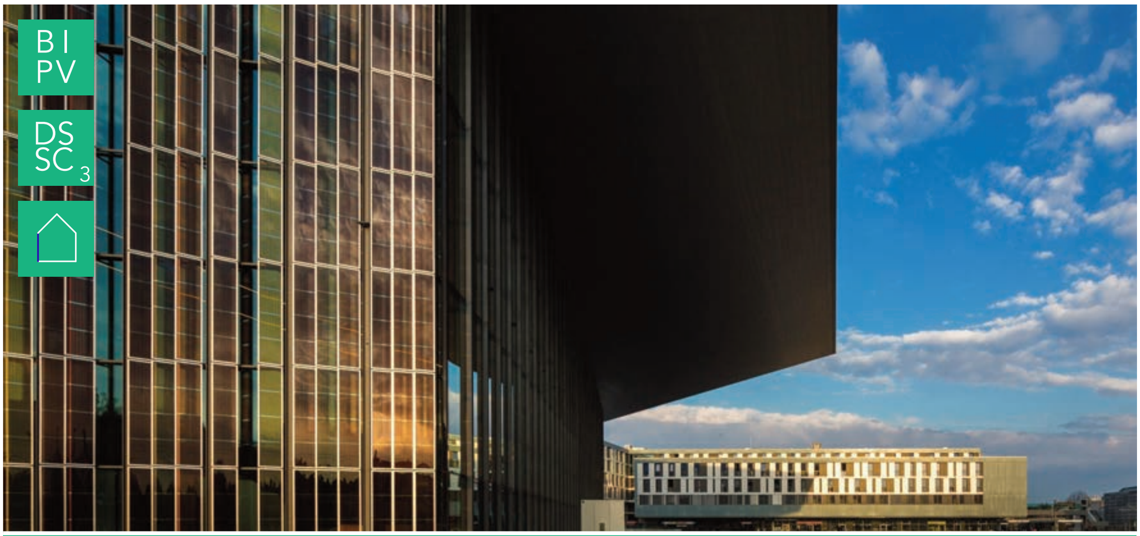


Specification on PV system

PV Product	Prosol PV Schüco
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	325 modules of 1.20 m side (125x125 mm)
Standard/Custom-made	Custom-made
Specifications	Triangular semi-transparent PV glass is the external layer of insulating double glass with argon-filled cavity
PV Installation	**Building-integrated**
Sub-system	Top and Side Envelope
Assembly or component	Roof and Façade
Functional layer/element	Infill and sunlight attenuation element
Additional info	Triangular modules separated by silicon joints and supported by three-dimensional mesh steel structure
Fixed/Movable	Fixed
Orientation	0°, 90° west
Surface	205 m² (2.3% of the building skin surface)
Power installed	12.6 kW
Yearly production	n.g.
KWh/kWp year	n.g.

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	
Elements of innovation	
Module design	■
Module installation	■
Integration concept	■



n06

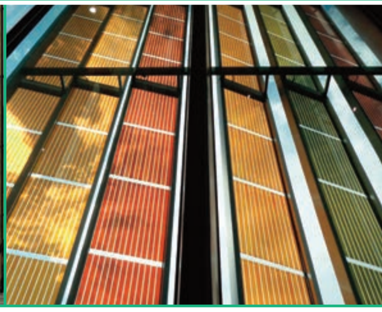
EPFL, Swiss Tech Convention Centre

Dahl Rocha & Associates Architects
Lausanne, Switzerland

World's first example of multi-colour DSC façade was installed on the south-west façade of the Swiss Tech Convention Centre, in the campus of EPFL, which is also the university where this solar technology was discovered in 1993. The DSC panels in 4 different colors are installed along 65 coloured and translucent strips on the glazed façade, tilted towards south according to different angles. The peculiarity of this PV integration is the interesting effect of the light that filters through the façade within building hall, «...bathing it in mystical light...». The artist Catherine Bolle was involved in the choice of the colour and in the design of the installation, collaborating directly with the PV manufacturer.

Building Facts

Year of completion:
2013
Context:
Development Area
Building Type:
Multipurpose Building
Energy Consultant:
Solaronix SA, Betelec SA, Romande Energie
Climate:
Maritime Temperate, Cfb
GHI: 1300 kWh/m² year


Specification on PV system

PV Product

PV Technology	Dye-sensitized Solar Cells
Cell Manufacturer	Solaronix, SA
Module Manufacturer	Solaronix, SA
Number, Dimensions	355 modules (0.35x0.50 m) form panels of 2-5 modules
Standard/Custom-made	Custom-made
Specifications	Aluminium-framed modules are laminated between glass panes. Colors: red, orange, two types of green

PV Installation — Building-integrated

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Sunlight attenuation element
Additional info	Panels are installed as external shading devices (preventing sunlight from overheating the hall) and are tilted towards south to increase PV productivity
Fixed/Movable	Fixed
Orientation	90°, south (with various azimuth)
Surface	300 m² (active area 200 m²)
Power installed	n.g.
Yearly production	Estimated 2,000 kWh/year
KWh/kWp year	n.g.

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation

Module design	■
Module installation	
Integration concept	■

n07

Novartis "Fabrikstrasse 15" Building

Gehry Partners
Basel, Switzerland

The skin of "Fabrikstrasse 15" building is largely made of curved glazing and forms a facade cavity around the five office floors creating a single air volume. The concept for this building satisfies exceptional comfort requirements and the client's low energy target of 83 kWh/m²year including heating, cooling, and electricity. The top envelope is cladded, for about 85% of its surface, by semi-transparent monocrystalline silicon panels on triple glass. The "perforated" configuration of the wafers allows filtering 12% of the natural light in the indoor environment, while generating the energy necessary to power artificial lighting for the building and avoiding around 32.5 tCO_2 every year.

Building Facts

Year of completion:
2009
Context:
Central Business District
Building type:
Multipurpose Building
Energy consultant:
Transsolar
Climate:
Maritime Temperate, Cfb
GHI:
1150 kWh/m² year

Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Sunways AG
Module Manufacturer	Schüco (installed by Tritec AG)
Number, Dimensions	125,000 wafers
Standard/Custom-made	Custom-made
Specifications	Panels on triple-glazing made of 12%-transparent silver cells, disposed according to a geometrical pattern

PV Installation — Building Integrated

Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	Infill and sunlight attenuation element
Additional info	Panels are supported by a welded, bending-resistant girder grid, allowing to follow building's irregular shape
Fixed/Movable	Fixed
Orientation	Variable, close to horizontal
Surface	1,300 m²
Power installed	93 kW
Yearly production	65,000 kWh/year
KWh/kWp year	701

Integration Criteria

Design Strategy

- Subjugation
- Domination
- Integration ■
- Subordination
- Imitation

Multifunctionality

- Multifunctional building/PV element ■
- PV with relevant aesthetic role ■

Bioclimatic features

- Solar and thermal protection ■
- Exploitation of conversion heat

Elements of innovation

- Module design ■
- Module installation
- Integration concept

n08

Oslo Opera House

Snøhetta A/S

Oslo, Norway

This award-winning project for Norwegian National Opera and Ballet in Oslo Harbour by Snøhetta is characterized by an external envelope made of Italian marble and glass and steel façades, tall up to 15 m. In the south façade, almost 6-sqm-wide PV panels with monocrystalline silicon wafers laid down according to parallel strips, covering 50% of their area, provide clean electricity and shading into indoor spaces. The strips become part of building aesthetic expression; indeed, they are replicated on the north side with dummy elements. PV was installed also to show this advanced technology to new audiences, taking advantage of the international recognition the building received.

Building Facts

Year of completion:
2007

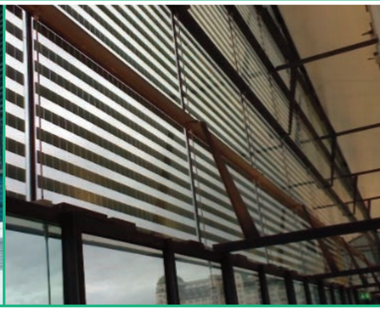
Context:
Central Business District

Building type:
Entertainment structure

Energy consultant:
Erichsen & Horgen AS

Climate:
Warm summer continental, Dfb

GHI:
900 kWh/m² year



Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	3.6 x 1.8 m
Standard/Custom-made	Custom-made
Specifications	Cells are arranged in horizontal strips, laminated between structural glass panes and part of double glazing

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Infill and sunlight attenuation element
Additional info	Load bearing horizontal steel elements and vertical cables were used to minimize vertical joints; this required structural glazing for modules also due to the large dimension
Fixed/Movable	Fixed
Orientation	90°, south
Surface	450 m² (50% active)
Power installed	35 kW
Yearly production	21,000 kWh/year (measured)
KWh/kWp year	600

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation

Module design	■
Module installation	■
Integration concept	

n09

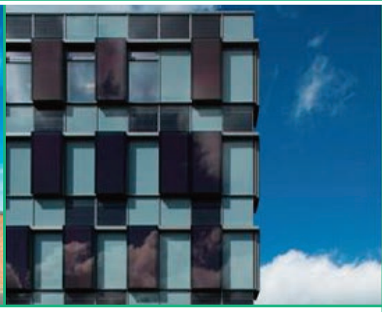
Energimidt

Aarstiderne Arkitekter
Silkeborg, Denmark

The new building of Energimidt (Danish utility providing advice on energy and particularly solar cells) had to meet all energy standards and be an attractive landmark showing how PV can be integrated in architecture. It has PV modules cladding the opaque parts of three façades and integrated into sliding shutters, a PV-integrated parapet, semi-transparent PV windows, and a “conventional” stand-off system on roof. A total power of 66.56 kWp is installed, producing about 45 kWh/year: this £2.5M investment is expected to be paid back in 10 years. Indeed, the compact building shape, the technical solutions for insulation and ventilation plus the PV systems make this building consume 70% less energy than building code requirements.

Building Facts

Year of completion:
2010
Context:
Development Area
Building Type:
Office Building
Energy Consultant:
Søren Jensen Rådgivende Ingeniør
Climate:
Maritime Temperate, Cfb
GHI:
950 kWh/m² year



Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	n.g.
Standard/Custom-made	Custom-made
Specifications	-

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding element (ventilated façade)
Additional info	Due to possible shading from other components, the upper part of the panels (installed on 3 sides of the building) is not active, except for the panels on the last floor
Fixed/Movable	Fixed
Orientation	90°, south, east and west
Surface	472 m²
Power installed	31.6 kW
Yearly production	18,700 kWh/year
KWh/kWp year	592

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

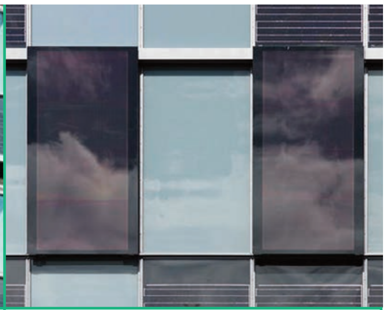
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection
Exploitation of conversion heat

Elements of innovation

Module design
Module installation
Integration concept



Specification on PV system

PV Product

PV Technology	Amorphous Silicon
Cell Manufacturer	Schott Solar
Module Manufacturer	Schüco
Number, Dimensions	90 modules (2.4x1.1 m)
Standard/Custom-made	Custom-made
Specifications	Modules are glass-glass frameless laminates, 25%-transparent, red/brown and have highly reflective surface

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Sunlight attenuation element
Additional info	Modules are integrated into sliding glass shutters, optimizing daylight level inside the offices and giving the building a variable expression during the day
Fixed/Movable	Movable
Orientation	90°, south, east and west
Surface	Approx. 255 m²
Power installed	9 kW (100 W per shutter)
Yearly production	n.g.
KWh/kWp year	n.g.

Integration Criteria

Design Strategy

Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality

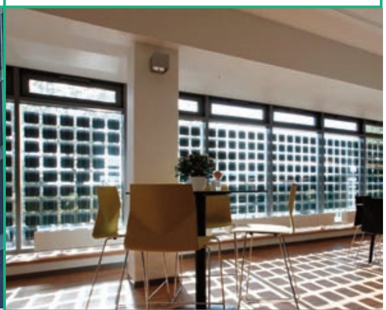
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation

Module design	
Module installation	■
Integration concept	■



Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	40 modules
Standard/Custom-made	Custom-made
Specifications	Frameless, light-through modules, laminated on low-iron glass pane of thermally insulating triple glazing

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Window
Functional layer/element	Infill and sunlight attenuation element
Additional info	Modules are fixed elements of the windows of the canteen (the upper non PV part is openable for ventilation) and of sky-lights on the roof, also reducing overheating and glare
Fixed/Movable	Fixed
Orientation	90°, south and east
Surface	20.4 m²
Power installed	2.88 kW
Yearly production	1,730 kWh/year
KWh/kWp year	601

Integration Criteria

Design Strategy

Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation

Module design	
Module installation	
Integration concept	

Specification on PV system

PV Product

PV Technology	Polycrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	25 modules
Standard/Custom-made	Custom-made
Specifications	Frameless semi-transparent modules, consisting of 2 layers of low-iron glass (both 5mm thick) laminated with solar cells distanced of 3 mm

PV Installation — Building Integrated

Sub-system	External Vertical Divider
Assembly or component	Parapet
Functional layer/element	Element of protection from falls
Additional info	Modues are integrated into the parapet of the balcony of the building, placed on its south-west corner
Fixed/Movable	Fixed
Orientation	90°, west and south
Surface	n.g.
Power installed	1.9 kWp
Yearly production	n.g
KWh/kWp year	n.g.

Integration Criteria

Design Strategy

- Subjugation
- Domination
- Integration ■
- Subordination
- Imitation

Multifunctionality

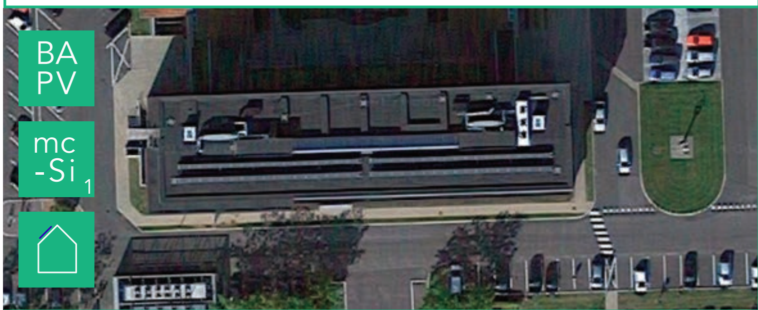
- Multifunctional building/PV element ■
- PV with relevant aesthetic role ■

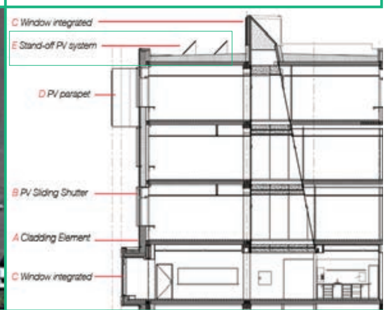
Bioclimatic features

- Solar and thermal protection
- Exploitation of conversion heat

Elements of innovation

- Module design
- Module installation
- Integration concept





Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Schüco
Module Manufacturer	Schüco
Number, Dimensions	n.g
Standard/Custom-made	Standard
Specifications	-

PV Installation — Building Added

Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	-
Additional info	Stand-off PV system on the roof, arranged in two separate rows
Fixed/Movable	Fixed
Orientation	30°, south
Surface	86.8 m^2
Power installed	12.58 kWp
Yearly production	11,455 kWh/year
KWh/kWp year	911

Integration Criteria

Design Strategy

- Subjugation ■
- Domination
- Integration
- Subordination
- Imitation

Multifunctionality

- Multifunctional building/PV element
- PV with relevant aesthetic role

Bioclimatic features

- Solar and thermal protection
- Exploitation of conversion heat

Elements of innovation

- Module design
- Module installation
- Integration concept

BA PV

CIGS 2

n10

Soft House

Kennedy & Violich Architecture, 360grad+architekten
Hamburg, Germany

This plus-energy housing prototype, presented in 2013 at the IBA Hamburg "Smart Material Houses" competition is characterized by a unique "dynamic structure", integrated with CIGS flexible modules. It is made of ribbon-like elements able to "track" the sun, conferring to the building a peculiar ever-changing architectural expression and maximized energy performance. On the roof, bendable boards tilt of angles varying upon weather conditions in order to follow the sun and maximize the energy output. On the façade, the boards are substituted by flexible elements that twist to respond to daily sunlight variations and optimize visual comfort. The wavy supporting construction integrates motors for twisters' activation.

Building Facts

Year of completion: 2013
Context: Development Area
Building Type: Residential Building
Energy Consultant: Büro Happold
Climate: Maritime Temperate, Cfb
GHI: 1000 kWh/m² year

Specification on PV system

PV Product	PowerFLEX™ BIPV - 300W
PV Technology	Copper Indium Gallium Diselenide (CIGS)
Cell Manufacturer	Global Solar® Energy Inc.
Module Manufacturer	Global Solar® Energy Inc.
Number, Dimensions	32 modules, 500x6000x3 mm
Standard/Custom-made	Standard
Specifications	Flexible modules on stainless steel, clamped at the upper end and fixed along their length by welded brackets

PV Installation	Building Added
Sub-system	External Horizontal Divider
Assembly or component	Canopy
Functional layer/element	-
Additional info	Modules are fixed on strips in: fiberglass-reinforced plastic able to bend (roof); translucent PTFE able to twist (façade) to maximize sunshading and PV performance
Fixed/Movable	Movable
Orientation	Variable tilt and azimuth (south façade/roof installation)
Surface	96 m² (calculated)
Power installed	n.g.
Yearly production	24,000 kWh/year
KWh/kWp year	n.g.

Integration Criteria

Design Strategy	
Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	■
Integration concept	■

n11

Lehrter Station

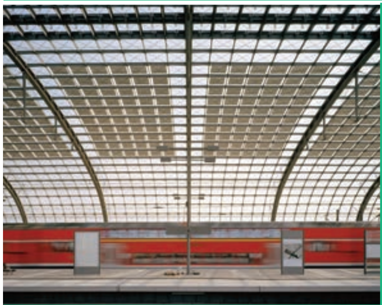
GMP Architekten

Berlin, Germany

This emblematic building (the largest railway station in Europe) is characterised by two multi-storey office buildings disposed as bridges above one sinuous element containing the platform hall, following the pathway of the trains. This element runs in east-west direction and is vaulted by a steel arch columnfree structure with glazed infills. Among them, 780 PV modules, whose shapes are slightly different among each other to adapt to the bent shape of the hall crowning, are integrated on its south and south-east sides, providing clean electricity production and sunlight attenuation. The promotion of architecturally integrated PV was one of the goals of this installation that is visible to thousands of people everyday.

Building Facts

Year of completion:
2002
Context:
Central City
Building Type:
Station
Energy Consultant:
BLS Energieplan GmbH
Climate:
Maritime Temperate, Cfb
GHI:
1050 kWh/m² year



Specification on PV system

PV Product	OPTISOL® M0611100K
PV Technology	Monocrystalline Silicon
Cell Manufacturer	BP Solar Limited
Module Manufacturer	FLABEG Solar International GmbH
Number, Dimensions	780 modules (each made of 100 cells), 2.5 m² each
Standard/Custom-made	Custom-made
Specifications	Frameless single glass PV laminates with specially developed plug and socket connection system, containing by-pass diodes and integrated in the joints
PV Installation	**Building Integrated**
Sub-system	External Horizontal Divider
Assembly or component	Canopy
Functional layer/element	Infill and sunlight attenuation element
Additional info	Panels are connected at the corners by metal fixing and jointed by rubber sealing elements
Fixed/Movable	Fixed
Orientation	Variable (7–19°), south and south-east
Surface	1,872 m² (active area 1,146 m²)
Power installed	189 kW
Yearly production	approx. 160,000 kWh/year (estimated)
KWh/kWp year	880 (estimated)

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	
Elements of innovation	
Module design	
Module installation	■
Integration concept	

n12

Power Tower, Energie AG Headquarters

Weber Hofer Architekten, Kaufmann and Partners

Linz, Austria

This 19-storey and 73 m high office tower in Linz does not make any use of fossil fuels or district heating. It is cladded for 2/3 in quadruple glazing (in some cases integrating sun slates for solar control) and for the remaining part in highly insulating materials. This minimizes the energy requirements for cooling and heating. Most importantly, the "Power Tower" also makes the most of the energy potential from soil, ground water and sun to reach its high energy standard and save about 450 t of carbon emissions yearly. The 638 m² blue PV façade is among the largest BIPV systems in Austria and helped this landmark tower reach his goal to become the first self-sustaining, passive-energy tower block in the world.

Building Facts

Year of completion:
2008

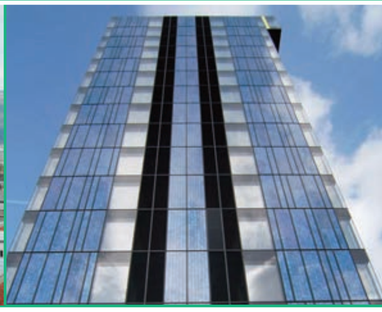
Context:
Central city

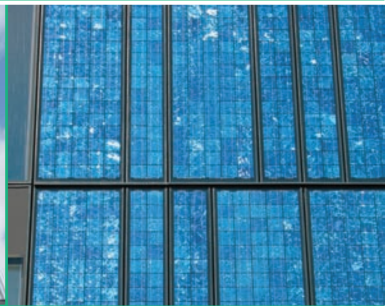
Building Type:
Office Building

Energy Consultant:
Kaufmann & Partner ZT-Gmbh

Climate:
Maritime Temperate, Cfb

GHI:
1150 kWh/m² year





Specification on PV system

PV Product	VSG
PV Technology	Polycrystalline Silicon
Cell Manufacturer	ERTL GLAS AG, ertex solar
Module Manufacturer	ERTL GLAS AG, ertex solar
Number, Dimensions	252 modules, in different sizes and formats
Standard/Custom-made	Custom-made
Specifications	Laminated safety glass modules with black frame. The height of the shiny blue modules is equal to the interfloor distance (3.71 m) and the width is variable
PV Installation	**Building Integrated**
Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding element (ventilated façade)
Additional info	The PV modules are rear ventilated and present a 18-cm thick insulation layer in rock wool on their rear side
Fixed/Movable	Fixed
Orientation	90°, south-west
Surface	638 m²
Power installed	66 kW
Yearly production	42,000 kWh/year
KWh/kWp year	636

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	
Elements of innovation	
Module design	
Module installation	■
Integration concept	■

n13

Low energy Aarhus Municipality building

C. F. Møller

Aarhus, Denmark

This 1800 m² office building was designed with the aim to become a landmark in the city of Aarhus as regards of the use of solar energy. In the words of the architect, solar components were incorporated as «...*sculptural elements in the façade, so that the building stands out as a distinctive image of energy architecture...*». Built according to the Passiv Haus standards and requiring less than 50 kWh/m² year, it presents over 200 m² PV system and, on the south-west corner, a 170 m² solar wall pre-heating air in winter and cooling the building in summer. Due to the limited budget, one type of standard PV panel (with fixed dimensions) was used and integrated in the façades of the building, in two different modalities.

Building Facts

Year of completion:
2010

Context:
Development Area

Building Type:
Office Building

Energy Consultant:
Alectia

Climate:
Maritime Temperate, Cfb

GHI:
950 kWh/m² year

Specification on PV system

PV Product	HEM150 M
PV Technology	Monocrystalline Silicon
Cell Manufacturer	HEM Photovoltaic, Danish Solar Energy Ltd.
Module Manufacturer	HEM Photovoltaic, Danish Solar Energy Ltd.
Number, Dimensions	115 modules, 0.65x1.50 m
Standard/Custom-made	Standard
Specifications	Modules made of 55 black monocrystalline wafers on white hardened-glass substrate

PV Installation	Building Integrated
Sub-system	External Vertical Divider
Assembly or component	Sun-shading
Functional layer/element	Sunlight attenuation element
Additional info	PV modules act as sun-shading elements of a sloped external partition
Fixed/Movable	Fixed
Orientation	45°, south
Surface	Approx. 112 m²
Power installed	16.8 kW
Yearly production	Approx. 115,000 kWh
KWh/kWp year	950

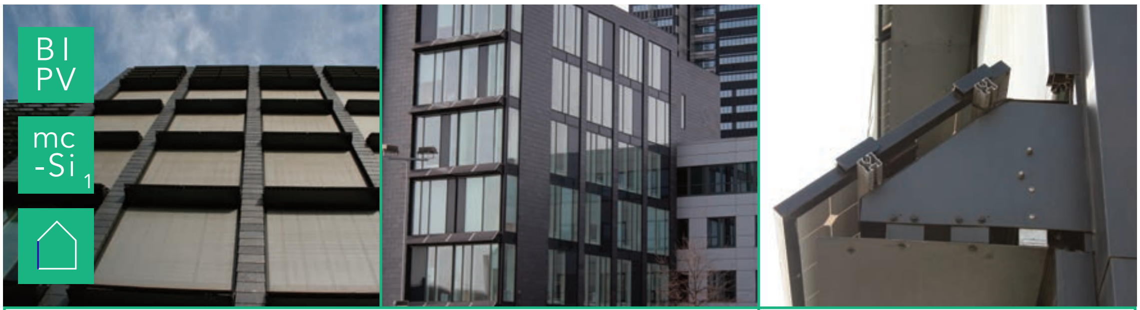
Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	
Integration concept	■



Specification on PV system

PV Product	HEM150 M
PV Technology	Monocrystalline Silicon
Cell Manufacturer	HEM Photovoltaic, Danish Solar Energy Ltd.
Module Manufacturer	HEM Photovoltaic, Danish Solar Energy Ltd.
Number, Dimensions	115 modules, 0.65x1.50 m
Standard/Custom-made	Standard
Specifications	Modules made of 55 black monocrystalline wafers on white hardened-glass substrate

PV Installation	Building Integrated
Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding element
Additional info	Modules are installed as cladding layer of the shades of façade glazing, also integrating vertical user-controlled sun-screens
Fixed/Movable	Fixed
Orientation	45°, south and south-east
Surface	Approx. 101 m^2
Power installed	15.2 kW
Yearly production	Approx. 114,000 kWh
KWh/kWp year	920

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	
Integration concept	■

n14

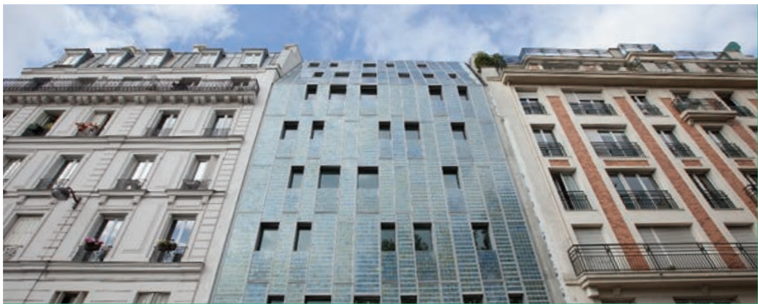
Social Housing in Quay de Valmy

Emmanuel Saadi and Jean-Louis Rey
Paris, France

This 7-storey building for social housing received a lot of attention from the public for being the first in Paris with a whole PV façade but also for its highly recognizable appearance. The blue-green cells, slightly less performing than typical dark-blue ones, had to receive the approval of the *Architectes des bâtiments de France*, given the building position in front of the historical Canal Saint-Martin. PV glasses in 70 different types were installed according to vertical strings of various sizes, as both cladding elements and parapets, in the openings. Selling the produced energy (40% of building needs) can lead to earnings of 3,500€/year. Thanks also to a ST roof-top installation, the building achieved a very high energy performance (79 kWh/m²/year).

Building Facts

Year of completion:
2011
Context:
Central City
Building Type:
Residential Building
Energy Consultant:
SIBAT s.a.r.l.
Climate:
Maritime Temperate, Cfb
GHI:
1100 kWh/m² year



Specification on PV system

PV Product	**VSG 6/6**
PV Technology	Polycrystalline Silicon
Cell Manufacturer	Sunways AG
Module Manufacturer	ERTL GLAS AG, ertex solar
Number, Dimensions	Approximately 130 modules, in 70 different types
Standard/Custom-made	Custom-made
Specifications	Frameless modules, with blue-green cells on safety glass subtrate with white-colored or transparent substrate
PV Installation	**Building Integrated**
Sub-system	Side Envelope
Assembly or component	Façade / Parapet
Functional layer/element	Cladding Element / Protection Element
Additional info	Module installed as cladding element of ventilated façade and parapet of apartments openings. Point fixings are hidden behind continuous joint cover plates
Fixed/Movable	Fixed
Orientation	90° and 60° (in the upper part of the façade), south-west
Surface	180 m²
Power installed	15.5 kW
Yearly production	7,000 kWh (40% of building electricity need)
KWh/kWp year	452

Integration Criteria

Design Strategy	
Subjugation	
Domination	■
Integration	
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	■
Elements of innovation	
Module design	
Module installation	■
Integration concept	■

n15

The House of Music

Coop Himmelb(l)au

Aalborg, Denmark

The House of Music counts of concert halls and education spaces related to music. The articulated exterior of the building caused quite a debate (some gave it the not so flattering epithet "cheese"). The south façade presents a sun-shading element with aluminium structure, where variously tilted triangular elements in perforated aluminum and semi-transparent PV modules are grouped, creating triangles of different sizes. Due to the presence of a 13-storey building on the other side of the road, the PV modules result partially shaded during some hours of the day. However, the manufacturer refers, in this case, to a «*...sustainable art installation...*», underlining the relevance of the aesthetic effect (probably more than a maximized efficency).

Building Facts

Year of completion:
2014

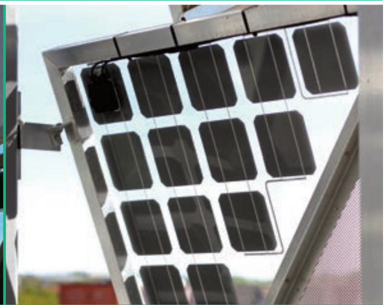
Context:
Central city

Building Type:
Entertainment structure

Energy Consultant:
Niras A/S

Climate:
Maritime Temperate, Cfb

GHI:
950 kWh/m² year



Specification on PV system

PV Product	Gaia Solar BIPV Glass/Glass modules
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Gaia Solar A/S
Module Manufacturer	Gaia Solar A/S
Number, Dimensions	263, in three different variations
Standard/Custom-made	Custom-made
Specifications	Semi-transparent, frameless, triangular modules with point fixing, occurring by means of screws

PV Installation	Building Integrated
Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Sunlight attenuation element
Additional info	Added sun-shading façade, consisting of a custom-made aluminum structure by HSHansen A/S, with slightly tilted perforated aluminum and PV elements
Fixed/Movable	Fixed
Orientation	Approximately 60°, south
Surface	-
Power installed	16.3 kWp
Yearly production	-
KWh/kWp year	-

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	■
Integration concept	■

n16

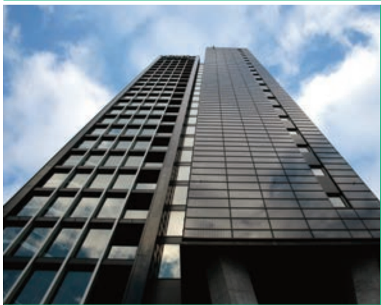
Crowne Plaza Copenhagen Towers

Dissing+Weitling
Copenhagen, Denmark

This 72,500 m² hotel and conference complex is made of 3 blocks: a 25-story tower almost entirely cladded in black mc-Si PV elements and two smaller blocks of 5 and 7 levels. The one located on the south side also presents a stand-off PV system on its roof. The PV-integrated system allowed exploiting most of the available surfaces with an internationally acknowledged result (e.g. EcoTourism Award as the world's greenest hotel). Also thanks to Denmark's first groundwater-based cooling/heating plant, this CO_2-neutral building achieved the EU Green Building Certification and Danish Building Regulation's low-energy class 2, rapidly becoming one of the favorite venues for conferences and events on sustainability in the city.

Building Facts

Year of completion:
2009
Context:
Development Area
Building type:
Commercial Building
Energy consultant:
Midtconsult and Gaia Solar A/S
Climate:
Maritime Temperate, Cfb
GHI:
1000 kWh/m² year



Specification on PV system

PV Product	**Gaia Solar BIPV Glass/Glass modules**
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Gaia Solar A/S
Module Manufacturer	Gaia Solar A/S
Number, Dimensions	2,500 modules in 38 different formats
Standard/Custom-made	Custom-made
Specifications	Glass/glass, with black backsheet, tempered glass in the front and sealed with EVA
PV Installation	**Building Integrated**
Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding element (ventilated façade)
Additional info	PV modules are installed with continuous elements, evidencing horizontal joints
Fixed/Movable	Fixed
Orientation	90°, south, east and west
Surface	1,700 m²
Power installed	200 kW
Yearly production	107,000 kWh/year
KWh/kWp year	535

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	
Elements of innovation	
Module design	■
Module installation	
Integration concept	

case studies **RETROFIT/RENOVATION**

r01	*Kollektivhuset*, Domus Architects, Copenhagen (Denmark)	2002
r02	*Solgården*, Kjær & Richter A/S, Kolding (Denmark)	1998
r03	*CIS Tower*, Solarcentury, Manchester (UK)	2004
r04	*SCHOTT Iberica Building*, Torsten Masseck, Barcelona (Spain)	2005
r05	*KTH Auditorium*, Stadion Architekter, Stockholm (Sweden)	2008
r06	*Mixed use building in Blutenburgstrasse*, a+p arkitekten, Munich (Germany)	2008
r07	*Bauhaus Building*, Brenne Winfried (original design by W. Gropius), Dessau (Germany)	2003
r08	*Paolo VI Audience Hall*, Fabrizio Viola (original design by P. Nervi), Vatican City (Vatican)	2007
r09	*Hôtel industriel "Le Losserand"*, Emmanuel Saadi and Jean-Louis Rey, Paris (France)	2014
r10	*The Opus House*, opus Achitekten, Darmstadt (Germany)	2007
r11	*Andreas Bjørnsgade Building,* Krydsrum Arkitekter, Copenhagen (Denmark)	2013

r01

Kollektivhuset

Domus Architects

Copenhagen, Denmark

Kollektivhuset is a residential building for disabled tenants, retrofitted in the field of the European project PV Nord. The SW balconies, situated in front of a high-traffic road, were closed through the installation of a PV-integrated glazed façade, providing thermal and acoustic insulation and generating electricity. Each apartment is provided of a system of 2 PV panels (extendable according to inhabitants' need). Glasses in different colors can slide to open or close the space on the rear of the panels, in order to let in (winter) or keep out (summer) the heat developed in the electric conversion: a passive strategy for heating/cooling also conferring a new, multi-color, variable look to the façade.

Building Facts

Year of retrofit:
2002 (original construction, 1959)
Context:
Suburb
Building type:
Residential building
Energy consultant:
Esbensen Consulting Engineers
Climate:
Maritime Temperate, Cfb
GHI:
1000 kWh/m^2 year

Specification on PV system

PV Product	
PV Technology	Monocrystalline Silicon
Cell Manufacturer	Gaia Solar A/S
Module Manufacturer	Gaia Solar A/S
Number, Dimensions	224 modules (8,064 cells), approximately 0.6x1.3 m
Standard/Custom-made	Custom-made
Specifications	Frameless solar cells laminated to a sheet of toughened glass with EVA and transparent Tedlar

PV Installation	Building Integrated on new volume
Sub-system	External Vertical Divider
Assembly or component	External partition wall
Functional layer/element	Infill element and element of protection from falls
Additional info	Glasses in various colors are installed behind PV panels and can slide to exploit/dissipate conversion heat
Fixed/Movable	Fixed
Orientation	90°, south-west
Surface	166 m^2
Power installed	10.1 kW
Yearly production	8,100 kWh/year
KWh/kWp year	802

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

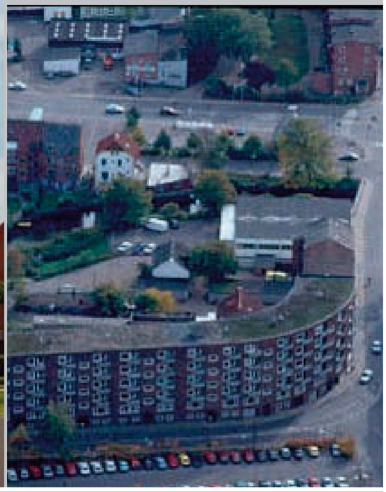
Bioclimatic features

Solar and thermal protection	
Exploitation of conversion heat	■

Elements of innovation

Module design	
Module installation	■
Integration concept	■

BEFORE RENOVATION



r02

Solgården

Kjær & Richter A/S
Kolding, Denmark

Solgården is an 80-apartment residential building, built in 1938. Two PV systems were installed on it in the occasion of its renovation in the 90s: one is integrated into the glazed balcony parapets (substituting the pre-existing niches); the other is a highly recognizable stand-off PV system, divided into four wings that follow the curved geometry of the building, and designed to seem floating on the roof. The systems are a part of a demonstration project in the field of a Kolding renewal program, that was meant to demonstrate the potential of PV in urban areas. At the time of completion, Solgården had the largest PV system on a building in northern Europe. Today it is used by a local producer of inverters as test site for new products.

Building Facts

Year of retrofit:
1998 (original construction, 1938)
Context:
Central city
Building type:
Residential building
Energy consultant:
C. J. Kjærby
Climate:
Maritime Temperate, Cfb
GHI:
1000 kWh/m² year

Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Pilkington (Siemens & Eurosolar)
Module Manufacturer	Pilkington (Siemens & Eurosolar)
Number, Dimensions	80 modules
Standard/Custom-made	Custom-made
Specifications	Wafers are arranged in horizontal stripes characterized by two rows of wafers; panels' rear glass is translucent

PV Installation — Building Integrated on new volume

Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Element of protection from falls
Additional info	Modules are installed as parapets of the glazed balconies that can either be opened or closed and were obtained by enlarging the former façade niches
Fixed/Movable	Fixed
Orientation	90°, variable due to curve building shape (south-east)
Surface	175 m²
Power installed	16 kW
Yearly production	-
KWh/kWp year	-

Integration Criteria

Design Strategy

Subjugation
Domination
Integration ■
Subordination
Imitation

Multifunctionality

Multifunctional building/PV element ■
PV with relevant aesthetic role ■

Bioclimatic features

Solar and thermal protection
Exploitation of conversion heat

Elements of innovation

Module design ■
Module installation
Integration concept


Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Pilkington (Siemens & Eurosolar)
Module Manufacturer	Pilkington (Siemens & Eurosolar)
Number, Dimensions	-
Standard/Custom-made	Standard
Specifications	Silicon wafers are laminated between two layers of clear glass

PV Installation — Building-added

Sub-system	Top envelope
Assembly or component	Roof
Functional layer/element	-
Additional info	System installed on racks allowing for: maintenance; optimum rear ventilation; covering of the 8 equipment cabinets (housing 104 inverters); plant "floating" appearance
Fixed/Movable	Fixed
Orientation	30°, variable due to curve building shape (south-east)
Surface	757 m^2
Power installed	90 kW
Yearly production	89,500 kWh/yr (calculated)
kWh/kWp year	994

Integration Criteria

Design Strategy

Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation

Module design	
Module installation	■
Integration concept	■

BI PV

pc -Si 1

BEFORE RENOVATION

r03

CIS Tower

Solarcentury (original design by Tait G., Hay C.S.)

Manchester, UK

The building of the British insurance company CIS Ltd. was the highest in Europe when it was built in 1962. After 40 years of pollution, the 14 million little mosaic tiles covering its windowless façade were falling off and the building required a significant renovation that costed around £5.5 M and was co-funded by public entities. Three façades of this listed building were clad with blue weatherproof solar panels, feeding into the National Grid. This allowed offsetting building material cost of replacing the traditional mosaic tiles. The building-mounted solar plant is Europe's largest vertical solar array. It is worth to note that 10% of the power consumed by the tower is also supplied by 24 wind turbines on the roof.

Building Facts

Year of retrofit:
1962 (original construction 2004)

Context:
Central Business District

Building Type:
Office Building

Energy Consultant:
Solcentury, Arup

Climate:
Maritime Temperate, Cfb

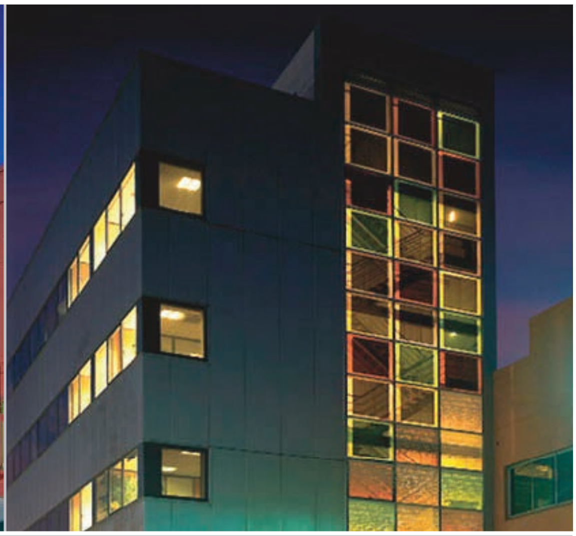
GHI:
900 kWh/m^2 year

Specification on PV system

PV Product	**Sharp 80W modules**
PV Technology	Polycrystalline Silicon
Cell Manufacturer	Sharp
Module Manufacturer	Sharp
Number, Dimensions	7,244 modules
Standard/Custom-made	Custom-made
Specifications	Framed modules (frame manufacturer: Pluswall): out of the 7,244 elements, in different dimensions, 870 are 'full size' and 109 'medium size' dummies
PV Installation	**Building Integrated**
Sub-system	Side Envelope
Assembly or component	Façade
Functional layer/element	Cladding layer (retrofitted ventilated façade)
Additional info	The new solar envelope is retrofitted on top of the existing one by means of an aluminium support structure
Fixed/Movable	Fixed
Orientation	90° on south-east, south-west, and north-west façades
Surface	3,972 m^2
Power installed	391 kW
Yearly production	183,000 kWh/year (avoided 100 tCO_2/year)
KWh/kWp year	468

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	
Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■
Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	
Elements of innovation	
Module design	
Module installation	
Integration concept	■



r04

Schott Iberica building

Torsten Masseck

Barcelona, Spain

Before its 2005 renovation, the 5-floor staircase located on the south-west façade of the Schott Iberica building was suffering from severe problems of overheating due to insufficient ventilation, lack of sunshading and poor thermal behavior. Multifunctional BIPV panels (see-through a-Si modules on colored glass substrate) were installed as windows, along with openable printed glasses placed on the lower part of the façade. PV substituted the previous fixed translucent glass infills that used to generate very high indoor temperatures (up to 50°C in summer). Thanks to this installation, coupled with an optimized natural ventilation strategy, the annual energy consumption dropped of about 8%.

Building Facts

Year of retrofit: 2008

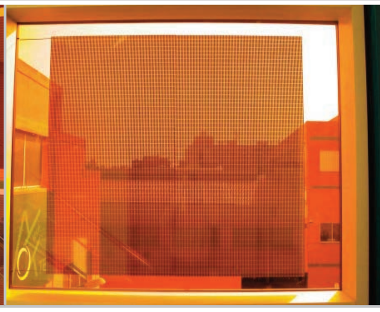
Context: Suburb

Building Type: Office Building

Energy Consultant: CISOL-Centre d'Investigació Solar, Universidad Politècnica de Catalunya

Climate: Warm Temperate, Cfa

GHI: 1600 kWh/m² year



Specification on PV system

PV Product	ASI® THRU Color
PV Technology	Amorphous Silicon
Cell Manufacturer	SCHOTT Solar
Module Manufacturer	SCHOTT Solar
Number, Dimensions	27 modules (50 Wp)
Standard/Custom-made	Standard
Specifications	10%-transparent modules on double glass (i.e. SCHOTT IMERA non-textured, body-tinted, colored glass substrate)

PV Installation	Building Integrated
Sub-system	Side Envelope
Assembly or component	Window
Functional layer/element	Infill and sunlight attenuation element
Additional info	Measurements showed that coloured glass cause cell temperature rise 10-15°C compared to a similar panel without coloured substrate
Fixed/Movable	Fixed
Orientation	90°, south-west
Surface	n.g.
Power installed	1.35 kW
Yearly production	1,270 kWh/year (measured in 2007)
KWh/kWp year	941

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation
Module design
Module installation
Integration concept

r05

KTH Auditorium

Stadion Architekter
Stockholm, Sweden

The KTH Royal Institute of Technology was originally built in 1948 and designed by the architects Nils Ahrbom and Helge Zimdahl as part of a larger group of buildings around a south-facing open courtyard. The corridor facing the courtyard was converted into a glazed entrance hall, requiring some shading in order to avoid overheating. Being an historically protected façade, external solar shading was not possible, thus the planners opted for the use of PV-integrated glazing in the form of spandrel panels, which were integrated in the windows. Solar cells were significantly distanced, i.e. of 40 mm: this provided the required amount of transparency, but caused a notable reduction in PV efficiency (4%).

Building Facts

Year of retrofit:
2008 (original construction 1948)
Context:
Central City
Building type:
Entertainment Structure
Energy consultant:
PO Andersson
Climate:
Maritime Temperate, Cfb
GHI:
900 kWh/m^2 year

Specification on PV system

PV Product

PV Technology	Polycrystalline Silicon
Cell Manufacturer	Saint-Gobain Glass Solar
Module Manufacturer	Saint-Gobain Glass Solar
Number, Dimensions	21 modules
Standard/Custom-made	Custom-made
Specifications	Glass-glass laminates

PV Installation — Building Integrated

Sub-system	Side Envelope
Assembly or component	Window
Functional layer/element	Infill and Sunlight Attenuation Element
Additional info	The integrated electricity cables are hidden by the ceiling. The electricity is immediately consumed, there is no storage in the system
Fixed/Movable	Fixed
Orientation	90°, south
Surface	28 m^2
Power installed	4.05 kW
Yearly production	1,450 kWh/year
KWh/kWp year	358

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation

Module design	
Module installation	
Integration concept	

r06

Mixed use building in Blutenburgstrasse

a+p arkitekten

Munich, Germany

In a urban context characterized by small-scale backyards, a vacant two-storey commercial building was renovated and the result was this four-storey mixed use building including 735 m² of offices, housing, and a large roof-top terrace. The building is open on the south-west side, where openings constitute 50% of its surface. Openings, in particular, are shaded by means of aluminium sliding shutters that are hidden behind CIGS panels. Vertical lines are accentuated through aluminium profiles and horizontal joints are in dark-colored silicon: this results in a homogeneous appeal. This elegant dark-blue PV installation perfectly matches the horizontality of the façade, given by the protruding white floor slabs.

Building Facts

Year of retrofit:
2004

Context:
Central City

Building type:
Residential and Office Building

Energy consultant:
Kulle and Hofstetter

Climate:
Maritime Temperate, Cfb

GHI:
1150 kWh/m² year

Specification on PV system

PV Product	Manz M-GCS123e090
PV Technology	Copper Indium Gallium Diselenide (CIGS)
Cell Manufacturer	Manz (ex Würth Solar)
Module Manufacturer	Manz (ex Würth Solar)
Number, Dimensions	56 modules, 1.2x0.6 m
Standard/Custom-made	Standard
Specifications	Dark blue glass-glass modules with shiny appeal, grouped in panels of 4 with highly "discreet" joints

PV Installation	Building Integrated
Sub-system	Side envelope
Assembly or component	Façade
Functional layer/element	Cladding element
Additional info	Modules are installed in front of a cavity that houses and conceals the shutters, while possibly optimizing the PV performance
Fixed/Movable	Fixed
Orientation	90°, south-west
Surface	41 m²
Power installed	3.9 kWp
Yearly production	2,000 kWh/year (about 1.2 tCO_2 avoided yearly)
KWh/kWp year	513

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation	
Module design	■
Module installation	■
Integration concept	

r07

Bauhaus Building

Brenne Winfried (original design by Walter Gropius)
Dessau, Germany

One of the aims of this intervention (supported by German government with €3.9M) was to show how it is possible to find a perfect balance between the conservation of a building listed as a World Cultural Heritage site and a significant energy upgrade. This upgrade, leading to savings for over 30%, consisted in measures highly respectful of the original design: substitution of façade single-glazing and uninsulated steel profiles with notably more efficient solutions; installation of new pumps, insulated heating ducts and an intelligent control system for the entire building; rooftop installation of a flat PV system, with uniform and discreet appearance, feeding electricity into the grid for an annual revenue of €16,400.

Building Facts

Year of retrofit:
2003 (original construction 1925-26)

Context:
Heritage Context

Building Type:
Listed Building

Energy Consultant:
Transsolar

Climate:
Maritime Temperate, Cfb

GHI:
1050 kWh/m^2 year

Specification on PV system

PV Product

PV Technology	Micromorph Silicon
Cell Manufacturer	Inventux Technologies AG
Module Manufacturer	Inventux Technologies AG
Number, Dimensions	-
Standard/Custom-made	Standard
Specifications	Thin, frameless modules, characterised by black and low-reflective surface appearance

PV Installation — Building Added

Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	-
Additional info	A very thin horizontal aluminum sructure with uniform black modules, matching the former roof colour, was chosen to avoid any impact on the Bauhaus architecture
Fixed/Movable	Fixed
Orientation	0°
Surface	272 m^2
Power installed	21.85 kW
Yearly production	19,000 kWh/year
KWh/kWp year	870

Integration Criteria

Design Strategy

Subjugation
Domination
Integration
Subordination ■
Imitation

Multifunctionality

Multifunctional building/PV element
PV with relevant aesthetic role

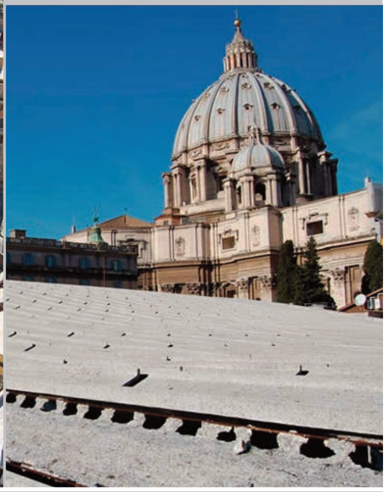
Bioclimatic features

Solar and thermal protection
Exploitation of conversion heat

Elements of innovation

Module design
Module installation
Integration concept

BEFORE RENOVATION



r08

Paolo VI Audience Hall

Fabrizio Viola (original design by Pier Luigi Nervi)
Vatican City, Vatican

This intervention on Paolo VI Audience Hall in Vatican City represents an emblematic case of PV implementation within a sensible heritage (Vatican city) and monumental building. This large PV plant was gifted by the solar manufacturers and was specifically designed to integrally replace the degraded concrete tiling of the building. In order to maximize PV area, two rows of tiles were replaced by one solar module, installed on the existing supporting structure by means of custom elements, made in aluminun with predisposed housing for module insertion. This plant received several awards and made of Vatican the nation with most PV power installed per capita in the world.

Building Facts

Year of retrofit:
2007 (original construction 1966)
Context:
Historical City
Building type:
Ceremonial Structure
Energy consultant:
Fabrizio Viola, Solar World AG
Climate:
Mediterranean, Csa
GHI:
1550 kWh/m² year

Specification on PV system

PV Product	
PV Technology	Monocrystalline Silicon
Cell Manufacturer	SolarWorld AG
Module Manufacturer	SolarWorld AG
Number, Dimensions	2,394 modules
Standard/Custom-made	Standard (with custom-made supporting structure)
Specifications	Framed modules on white plastic substrate with the dimensions of two of the former tiles juxtaposed

PV Installation	Building Integrated
Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	Finishing element
Additional info	Panels are coupled with grey reflectors on north-oriented rows that boost solar yield and are mounted on the existing supports of the replaced concrete tiles
Fixed/Movable	Fixed
Orientation	Variable tilt, south
Surface	2,012 m²
Power installed	221 kW
Yearly production	300,000 kWh/year (avoided 225 tCO_2/year)
KWh/kWp year	1,357

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation	
Module design	
Module installation	■
Integration concept	

r09

Hôtel industriel "Le Losserand"

Emmanuel Saadi and Jean-Louis Rey

Paris, France

This former sub-station of *Compagnie Parisienne de Distribution d'Électricité* has been transformed into an incubator of innovative companies. In the renovation, PV glass was installed to enclose and shade both the volume of the offices, built behind the existing building shell, and a new glazed meeting space located on the roof-top terrace, where PV glass is also installed on parapets. The building is expected to feed into the grid ca 80,000 kWh/year thanks to 45,000 cells (area: 1,800 m^2; active area: 1,000 m^2; power: 123.5 kWp). The "pixelated" PV façade replicates the texture of the natural stone that clads the building, establishing a relation with the existing and generating peculiar light effects, from inside to outside and vice versa.

Building Facts

Year of retrofit:
2007 (original construction, 1929)

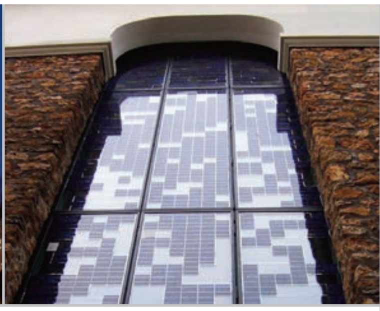
Context:
Inner city

Building Type:
Office building

Energy Consultant:
CSTB, Centre Scientifique et Technique du Bâtiment

Climate:
Maritime Temperate, Cfb

GHI: 1100 kWh/m^2 year



Specification on PV system

PV Product	Optisol® Screen
PV Technology	Polycrystalline Silicon
Cell Manufacturer	Photowatt SAS
Module Manufacturer	Scheuten Solar GmbH
Number, Dimensions	-
Standard/Custom-made	Custom-made
Specifications	Frameless modules on double-glazing with wafers distributed according to an irregular pattern derived from the pixelation of the natural stone cladding the building

PV Installation	Building integrated
Sub-system	Side Envelope
Assembly or component	Façade/Window
Functional layer/element	Infill and sunlight attenuation element
Additional info	Modules are in a slightly rearward position with respect to the existing building façade
Fixed/Movable	Fixed
Orientation	90°, south and east
Surface	1,150 m^2
Power installed	83.5 kWp (calculated)
Yearly production	-
KWh/kWp year	-

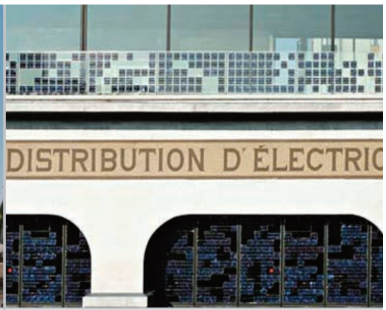
Integration Criteria

Design Strategy	
Subjugation	
Domination	■
Integration	
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	■
Module installation	
Integration concept	■



Specification on PV system

PV Product	Optisol® Screen
PV Technology	Polycrystalline Silicon
Cell Manufacturer	Photowatt SAS
Module Manufacturer	Scheuten Solar GmbH
Number, Dimensions	-
Standard/Custom-made	Custom-made
Specifications	Frameless modules on safety glass, installed with a thin supporting structure, also in this case with a random pattern generated from pixelation

PV Installation	Building integrated
Sub-system	External Vertical Divider
Assembly or component	Parapet
Functional layer/element	Element of protection from falls
Additional info	The thinness of the supporting structure gives the impression of continuity to this translucent, blue PV strip
Fixed/Movable	Fixed
Orientation	90°, south, east and west
Surface	130 m^2
Power installed	9.44 kWp (calculated)
Yearly production	-
KWh/kWp year	-

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation	
Module design	■
Module installation	
Integration concept	■

Specification on PV system

PV Product	Optisol® Screen
PV Technology	Polycrystalline Silicon
Cell Manufacturer	Photowatt SAS
Module Manufacturer	Scheuten Solar GmbH
Number, Dimensions	-
Standard/Custom-made	Custom-made
Specifications	Compared to the other positions of installation, a more opaque envelope is obtained by using modules, from which a smaller number of wafers is "subtracted"

PV Installation	Building integrated on new volume
Sub-system	Top and Side Envelope
Assembly or component	Roof and façade
Functional layer/element	Infill and sunshading element
Additional info	-
Fixed/Movable	Fixed
Orientation	0° and 90° east and west
Surface	420 m^2
Power installed	30.5 kWp (calculated)
Yearly production	-
KWh/kWp year	-

Integration Criteria

Design Strategy	
Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality	
Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features	
Solar and thermal protection	■
Exploitation of conversion heat	

Elements of innovation	
Module design	■
Module installation	
Integration concept	■

BEFORE RENOVATION

r10

The Opus House

opus Achitekten
Darmstadt, Germany

The award-winning Opus House is the result of the renovation of an early XX century building and of the closure of the adjacent vacant lot, in line with Passiv Haus standard. The newly built portion, cladded with high-performing triple glazing, was destined to offices, whereas the former two-storey building was dedicated to housing and provided with a new historicizing floor plus a contemporary style attic. Its sloped roof was entirely cladded with BIST (for half of the east roof) providing DHW and assisting the space heating and BIPV (for the remaining part) feeding the public grid. Detailing and appearance (colors, sizes, etc.) were chosen so that the roof blends harmoniously into the surrounding roofscape of metal and slate cover.

Building Facts

Year of retrofit:
2007 (original construction early 1900)

Context:
Inner city

Building Type:
Residential and Office Building

Energy Consultant:
inPlan Pfungstadt

Climate:
Maritime Temperate, Cfb

GHI:
1100 kWh/m² year



Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	Sharp
Module Manufacturer	Solea
Number, Dimensions	72 modules, 1000x1000 mm
Standard/Custom-made	Custom-made
Specifications	Frameless glass/plastic laminates with anthracite wafers and dark substrate for a more uniform appearance

PV Installation — Building Integrated on new volume

Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	Cladding Element
Additional info	Modules are provided with a rear ventilation cavity; solar PV and thermal collectors of identical size are mounted with the same modular grid and supporting structure
Fixed/Movable	Fixed
Orientation	32.5°, east and west
Surface	72 m²
Power installed	8.64 kW
Yearly production	7,500 kWh/year
KWh/kWp year	868

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection
Exploitation of conversion heat

Elements of innovation

Module design
Module installation
Integration concept

BEFORE RENOVATION

r11

Andreas Bjørnsgade Building

Krydsrum Arkitekter
Copenhagen, Denmark

This residential building of early XX century in Copenhagen historical centre was renovated by a multidisciplinary team of energy consultants, architects, engineers, developers with the collaboration of residents. The aim was not only to upgrade building performance, but also to demonstrate the possibility to integrate PV into ancient buildings worthy of preservation (it has been the first case in Copenhagen historical centre). The solution, provided after a series of tests and mock-ups, consists of precast elements in black c-Si roof panels, replacing the former roof finishing and reproposing its color. The rest of the roof surface is covered with matt black Trespa plates, guaranteeing a uniform appearance to the roof.

Building Facts

Year of retrofit:
2013 (original construction early 1900)
Context:
Historical city
Building type:
Residential Building
Energy consultant:
Energi+
Climate:
Maritime Temperate, Cfb
GHI:
1000 kWh/m² year

Specification on PV system

PV Product

PV Technology	Monocrystalline Silicon
Cell Manufacturer	EnergiMidt A/S
Module Manufacturer	-
Number, Dimensions	108 panels
Standard/Custom-made	Custom-made
Specifications	Uniform black panels for roof cladding, made of standardized elements

PV Installation — Building integrated

Sub-system	Top Envelope
Assembly or component	Roof
Functional layer/element	Cladding element
Additional info	The former roof was replaced by a new highly insulated one made of black PV and Trespa panels
Fixed/Movable	Fixed
Orientation	South-east and south-west
Surface	140 m² (roof area: 240 m²)
Power installed	20.3 kW
Yearly production	17,000 kWh/year; 19,000 kWh/year (measured), 27% of building needs
KWh/kWp year	936

Integration Criteria

Design Strategy

Subjugation	
Domination	
Integration	■
Subordination	
Imitation	

Multifunctionality

Multifunctional building/PV element	■
PV with relevant aesthetic role	■

Bioclimatic features

Solar and thermal protection	
Exploitation of conversion heat	

Elements of innovation

Module design	■
Module installation	
Integration concept	

Notes

1) The Task 41 of IEA:SHC program, "Solar Energy and Architecture" (cf. http://www.iea-shc.org/task41) detailedly reported the results of an international web-based survey involving over 600 architects from 14 countries and concerning the integration of solar energy systems and architecture. Among the various outcomes of this survey, it has been found that «…*despite an overwhelming interest in solar technologies and active solar design solutions, with 80% ranking it as important, only very few are applying it in their current architectural practice on a regular basis*…», cf. Farkas & Horvat, 2012.

2) «…*With regard to the visual integration of collectors and photovoltaic modules, architects are not alone in commenting on random component placement on the roof, the destruction of homogeneous surfaces, discrepancies in style, and the lack of proportion between the component dimensions and the smaller roof covering units, as reasons for poor quality in design*…»: Krippner, 2006.

3) Another aspect that indeed emerges from the survey in Farkas & Horvat (2012) is the lack of architecturally oriented literature regarding active solar technologies.

4) Which can not be taken into account when speaking of BAPV systems.

5) Cf. www.bipv.ch.

6) The 29 PVPS members are: Australia, Austria, Belgium, Canada, China, Denmark, EPIA, European Union, France, Germany, International Copper Association, Israel, Italy, Japan, Korea, Malaysia, Mexico, Netherlands, Norway, Portugal, SEIA, SEPA, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, United States. Cf. http://www.iea-pvps.org.

7) Programme of the International Energy Agency, started in 1977 and aimed to promote the use of all aspects of solar energy through the international collaborative effort of experts from member countries and the European Union (Cf. http://www.iea-shc.org).

8) Cf. http://task41.iea-shc.org/description

9) The criteria were developed also by starting from the results of a thorough web survey submitted to a pool composed mainly by architects, but also of engineers and PV manufacturers; the interviewees were asked to rate the integration quality of different examples of solar thermal applications in buildings. Cf. Munari Probst, 2008.

10) However — as the author herself underlined — interviewees, and in particular architects, consistently agreed on the value of integration quality, be it good or bad, with only some slight differences, meaning the existence of a common understanding of the architectural integration quality, independently from the codification of some specific criteria. Cf. Munari Probst, 2008.

11) Munari Probst (2008) also underlined how, within the survey conducted, the best rated examples were also those were modules were used as multifunctional building components.

12) The research involved the Department of Architecture and Building Engineering (DICEEA) of the University of L'Aquila and the Swiss BIPV competence centre of SUPSI (Scuola Universitaria Professionale della Svizzera italiana).

13) The three tables are reprised from Bonomo & De Berardinis, 2012; for a more detailed description of the criteria, please refer to: Di Gianni & Bonomo (2011) and Bonomo (2012).

14) «…*The integration of PV contributes to spatial and linguistic innovation of architectural design, through the rethinking of forms and functions of the envelope and of the interior spaces and through the emergence of innovative design concept*…», Di Gianni & Bonomo (2011).

15) The results of one of the first applications of this methodology to a number of well-known case studies have been discussed in Bonomo, De Berardinis, & Frontini (2013).
16) The 5 Decrees — also known as Conto Energia — enacted the European Directive 2001/77/CE of the European Parliament and of the Council, September 27th, 2001, on the promotion of electricity produced from renewable energy sources in the internal electricity market.
17) In particular, this work is inserted within the project SuRHiB - Sustainable Renovation of Historical Buildings (cf. http://www.ccem.ch/surhib) and, in its regard, it should be underlined that the authors were providing some as objective as possible guidelines by mainly referring to non-protected historical buildings in historical town centers in Ticino. Cf. Polo Lopéz & Frontini, F., (2011).
18) French manufacturer of photovoltaic and solar thermal systems (Cf. www.clipsol.com).
19) In the previous example (Phare de Poulains), a «...perfectly integrated...» (Nagel and Zanetti) solution from the constructional point of view does not result convincing nor compatible with respect to the existing building from an aesthetic point of view. In different contexts and on different buildings, similar solutions are praised as highly integrated both constructionally and aesthetically.
20) Both buildings are deeply analysed as case studies (see sheets r02, r07);
21) Speaking of the relation between photovoltaics and architecture, other works (Scognamiglio, 2010) have referred to the concept of *"discreetness*" to describe those buildings that look for the public approval rather than provoking their awe («...*cercano il consenso del pubblico piuttosto che volerne provocare lo stupore...*», p. 137) and associated this design concept with the adoption of solutions that are replicable and easy to standardize.
22) Energi+ involves Krydsrum Arkitekter (www.krydsrum.dk), Rönby.dk (ww.rönby.dk) and EKOLAB (www.ekolab.dk); the partners of the project were also: Københavns Kommunes Center for Bydesign (Centre for Urban Design of the Copenhagen Municipality), EnergiMidt (www.enegimidt.dk) e Enemærke & Petersen (ww.eogp.dk).
23) Cf. http://renover.dk/projekt/ef-andreas-bjoerns-gade-1. The building is also deeply analysed in the sheet r11.
24) According to CasaClima certification scheme, *Classe A* is a building that needs less than 30 kWh/m²year.
25) The building is deeply analysed in the case study sheet n01.
26) www.arup.com;
27) The author acknowledges Architect Lars Kvist, from Arkitema Architect, for the interesting conversation and the information provided for the study of this building.
28) For example, nowadays several regulations subsidize massively building-integrated products and application (e.g. Switzerland, France...).
29) The building is deeply analysed in the case study sheet r01.
30) During rush hours more than 30,000 Copenhagen citizens pass the building. Cf. *Hans Knudsens Plads, Copenhagen, Denmark* (Report from PV nord project). Retrieved from http://www.pvnord.org)
31) It is worth also to note the particular solutions adopted in order to provide more flexibility for tenants who want to expand their two-panel system, based on their needs. «...*In ordinary projects the electrical wiring of the systems would be based on string wiring, where each floor of the building would be connected to one string inverter […] The string wiring is established in vertical zones fully integrated in the facade construction collecting the power from each panel […] so that further panels can be inserted at each balcony and directly connected to the string-wiring, allowing flexible expansion of the system...*». Cf. Report from PV nord project. Retrieved from http://www.pvnord.org. Moreover, the product used for the electrical connectors can be accessed directly from

each balcony without any risk of electrical shocks. Therefore, the installation of new panels can be carried out from the balcony, without requiring expensive scaffolding of the building and thus corresponding to lower installation (as well as maintenance) costs compared to traditional PV systems in high-rise buildings.

32) Cf. www.arkitema.dk;

33) The NSERC Solar Buildings Research Network completed its program at the end of 2010 and it has been substituted and expanded by the NSERC Smart Net-zero Energy Buildings strategic Research Network (SNEBRN), funded for 2011-2016. The network unites several partners among Canadian Universities, industrial companies and associations with the aim to make R&D in the field smart net-zero energy buildings. Cf. www.solarbuildings.ca;

34) SolarWall® by Conserval Engineering Inc., www.solarwall.com;

35) Custom polycrystalline modules, manufactured by Day4 Energy Inc., http://www.day4energy.com;

36) An annual solar energy production of 21,800 kWh was estimated in advance, by taking into account the given PV area (240 m^2) and the annual solar irradiation (981 kWh/m^2 per year) expected in Oldenburg. On-site measurements showed a continuous energy production of 20% over the initial estimate (cf. http://www.asp-stuttgart.de/asp_content.php?lan=en&n=2&s=0&d=2&id=27);

37) Federal Photovoltaic Award 2006; German Solar Award 2006; Cityscape Award of the City of Oldenburg 2006 (cf. http://www.asp-stuttgart.de/asp_content.php?lan=en&n=2&s=0&d=2&id=27).

38) Solar Decathlon is a competition held every two years and organized by the U.S. Department of Energy. It challenges «*…collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The winner of the competition is the team that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency…*». Cf. http://www.solardecathlon.gov/about.html. The competition was first inaugurated in 2002 and it is today at its 7th edition (October 2015, California).

39) Custom-made ASI® OEM Outdoor Solar Modules, in amorphous silicon, manufactured by Schott AG. Cf. www.schott.com;

40) The product that is presented and studied in the second part of this thesis — DSC-integrated glass block component — belongs to this family of multi-functional semi-transparent PV glazing products for the integration with the building envelope for both roof and/or façade applications.

41) http://www.ise.fraunhofer.de/en/front-page

42) The simulations involved the following softwares: CAD Nemetschek (http://www.allplan.com/it.html), ESP-r (a modelling tool for building performance simulation, http://www.esru.strath.ac.uk/Programs/ESP-r.htm), WINDOW (a tool for the energy performance calculation of window and glazing systems, http://windows.lbl.gov), Radiance (a set of tools for performing lighting simulations, http://radsite.lbl.gov/radiance). Cf. http://task41.iea-shc.org/casestudies. Case-study author: Margarethe Korolkow;

43) ASI THRU® Color by SCHOTT Solar, cf. www.schott.com;

44) «*…The individual wiring of the PV-panels, and combination of sliding back-panels and fixed front glazing is a unique concept in Europe. It is very likely, that the system will mark a new standard for providing PV to Scandinavian housing block tradition, where the tenants can be expected to have individual priorities and possibilities to further expanding their solar system…*». Cf. Report from PV nord project, Retrieved from http://www.pvnord.org.

45) Three-storey building consists into four units, extendable according to the "terraced house" principle, with apartments at the two top floors and offices at the ground floor (which can be independent from the flats and rented, thanks to separate access);
46) www.kvarch.net;
47) IBA Hamburg 2006-2013 (Internationale Bauausstellung, i.e. International Building Exhibition) is one of the largest urban development projects in Europe, carried out since 2006 with the aim to find answers to the most pressing issues modern cities are facing. Around 70 projects have been implemented in the city of Hamburg until 2013. Cf. http://www.iba-hamburg.de;
48) The tilting of the module allows for a 15% increase in modules' energy harvesting;
49) PowerFLEX™ BIPV - 300W by Global Solar® Energy Inc. Cf. www.globalsolar.com;
50) Cf. IBA Hamburg GmbH. (2013). *Smart Material House. Soft House*. (Project report). August 2013. Retrieved from www.iba-hamburg.de;
51) «*...With regard to the materials used, the thin-film photovoltaics installed have been a particular disappointment. The project team based their concept on the minimal use of materials, but with a high level of efficiency. The industry was working on solutions to fit, but as the crisis in the photovoltaics industry escalated it was no longer possible to develop new solutions for applying PV elements to the membranes in tandem with industry partners. It was therefore necessary to fall back on a standardised panel product...*». Cf. IBA Hamburg GmbH (2013).
52) The Energy Use Intensity (EUI) indicator is calculated by dividing the total gross energy (expressed in kWh) consumed in a year by the total gross square footage of the building.
53) Cf. IBA Hamburg GmbH. (2013);
54) «*...international practice dedicated to the pursuit of beauty and performance in the built environment...*» (http://sga-p.com).
55) Cf. www.arup.com
56) Suntech China, Suntech Power Holdings Co., Ltd., www.suntech-power.com
57) «*…The innovative use of technology and experimental approach to communication and social interaction defins new standards in the context of urban interventions worldwide, raising global interest in the integration of digital technology with architecture and reinforcing the reputation of Beijing as a centre for innovation and urban renewal…*», http://sgp-a.com.
58) A yearly production of 46,500 kWh was calculated (Rossetti 2011).
59) Talking of Green Pix, Simone Giostra underlined how «*...it promotes the uncompromised integration of sustainable technology in new Chinese architecture, responding to the aggressive and unregulated economic development currently undertaken by industry—often at the expense of the environment...*», cf. *GreenPix, Beijing's first Zero Energy Media Wall, designed by Simone Giostra & Partners with Arup, to launch June 24, 2008.* Press Realease, 2008. Retrieved from http://www.greenpix.com.
60) The Valby PV plan ("Sol i Valby") was launched in 2000, with the aim to supply, through PV, 10-15% of all electricity use in Valby by 2025, which is also the same year when Copenhagen has the ambition to become the first carbon neutral city on the planet. In order to reach this goal, the intentions of the group of associations and organizations involved in the launch of this program, partially funded by the EU, are to install approximately 30 MWp of PV power (a surface of about 300,000 m^2) in 25 years only in the Valby area, a peripheral developing district of the city of Copenhagen. Several projects have been implemented, involving both renovations and new constructions, where PV is of course one the main elements. Cf. http://www.solivalby.dk.

61) Vejsig Pedersen, P. (2014). *Photovoltaics Plan in Valby (Copenhagen) - Green Solar Cities* [Video]. Retrieved from http://vimeo.com/98926905;

62) Actually, the full name of the work is "Valbygavlen. En port till Kobenhavn", literally "The gable of Valby. A Gate for Copenhagen".

63) http://task41.iea-shc.org/casestudies. Case study author: Doris Ehrbar.

64) Other works have analyzed this aspect, among which: Baum & Liotta (2011); Baum (2011); Scognamiglio (2009).

65) Although in the digital world the adjective pixelated is often associated with low-resolution, low-quality images, the pixelation has been a place of wide experimentation in architecture (Balik, 2015) for the transferring onto building surfaces of more or less complex images.

66) For example, through the perforation of the cladding elements (e.g. De Young Museum, Herzog & De Meuron, San Francisco), the association of elements of different colors (e.g. Hainburg Nursing Home, Christian Kronaus and KNOWSPACE architecture + cities, Hainburg), the alternation of solids and voids (e.g. VINORAMA, Atelier Daniel Schlaepfer, Rivaz). Cf. Bartolacci, 2013.

67) The two buildings just mentioned (Cité du Design, Hotel Industriel Le Losserand) are deeply analysed in the case-study sheets n05 and r09, respectively.

68) The product used is "ThyssenKrupp Solartec", a complete roofing and façade system comprising UNI-SOLAR® solar film laminated onto galvanized and plastic-coated steel sheet, including the ReflectionsOne® color collection from ThyssenKrupp Steel (cf. www.reflectionsone.de/en/referenzprojekte/solarfassade.jsp).

69) Some of the most relevant references, where more consistent collections of case-studies can be found, are: www.bipv.ch; www.pvdatabase.com; www. solarfassade.info; task41.iea-shc.org/casestudies; Weller et al., 2010.

70) The author would like to acknowledge Karin Kappel, Architect and Head of Secretariat of the Association Solar City Denmark (working to ensure that Denmark has an international role in the development of solar energy projects with high architectural and technical quality, http://www.solarcitydenmark.dk) for the support in the collection of information regarding Danish Case studies and the contacts provided.

71) In order to be as exact as possible, the definitions for 'Context' and 'Building Typology' of each case-study were selected within the Getty Art & Architecture Thesaurus, AAT, (http://getty.edu), which is «...*a structured vocabulary, including terms, descriptions, and other information for generic concepts related to art, architecture, conservation, archaeology, and other cultural heritage*...».

72) It was first published by Russian German climatologist Wladimir Köppen in 1884, with several later modifications by Köppen himself, notably in 1918 and 1936. Later, German climatologist Rudolf Geiger collaborated with Köppen on changes to the classification system, which is thus sometimes referred to as the Köppen–Geiger climate classification system.

73) The climate data for each building site have been obtained by using the Köppen-Geiger climate classification maps available as KMZ file, openable in Google Earth and retrieved from http://koeppen-geiger.vu-wien.ac.at.

74) Cf. www.solarGIS.info.

75) Annual average GHI for each building site were obtained from the solar maps available at www.solarGIS.info.

76) Referring to the technological breakdown of the building system, according to ISO 6241.

77) The following four possibilities are acknowledged: Building-integrated; Building-integrated on newly-added volumes; Building-added; Building-added on newly-added volumes.

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PART II

Study and Development of
Novel Translucent BIPV Components

CHAPTER 4
Novel Translucent Glass Block Components for BIPV
Componenti innovativi in vetromattoner per il BIPV

ABSTRACT_ITA - *Il vetromattone è un prodotto edilizio ben noto che ha trovato una vasta applicazione, nel panorama dell'architettura moderna e contemporanea, per la realizzazione sia di partizioni interne ed esterne che di involucri edilizi. La necessità di ottimizzarne le prestazioni energetiche secondo le sempre più stringenti normative in materia di efficienza energetica negli edifici e di renderlo maggiormente competitivo ha condotto a numerosi tentativi finalizzati, da un lato, al miglioramento delle sue prestazioni di isolamento termico e trasmissione luminosa, dall'altro, all'ottimizzazione dei convenzionali sistemi di assemblaggio per installazioni sia interne sia esterne, basati su processi "ad umido" che fanno uso di malta cementizia.*

Alla luce di queste considerazioni e a partire dalle valutazioni contenute nella prima parte del presente lavoro, un componente edilizio innovativo, traslucido e multifunzionale per il BIPV viene qui presentato e descritto nel dettaglio. Questo componente, sviluppato presso il Dipartimento di Architettura dell'Università di Palermo, è un pannello preassemblato a secco e precompresso, costituito da vetromattoni innovativi, ottimizzati dal punto di vista dell'isolamento termico e integrati con celle solari di terza generazione (Dye-sensitized Solar Cells, DSC). All'interno del capitolo sono descritte quattro configurazioni brevettate del vetromattone integrato con DSC, che rappresentano essenzialmente le principali posizioni possibili dei moduli solari all'interno del prodotto. Si riportano anche alcuni degli studi condotti all'Università di Palermo per la definizione tecnologica del sistema di assemblaggio a secco dei vetromattoni, caratterizzato dall'impiego di profili di supporto in materiale plastico e da elementi di irrigidimento costituiti da barre di acciaio pretensionate.

Il capitolo, inoltre, contiene una breve analisi della letteratura riguardante l'utilizzo di elementi fotovoltaici semi-trasparenti per la realizzazione di involucri edilizi in grado sia di produrre energia sia di contribuire al risparmio energetico degli edifici, nonché un quadro delle potenzialità e delle sfide derivanti dall'utilizzo del colore nell'ambito degli involucri traslucidi. All'interno dell'ambito così delineato si inseriscono, infine, alcune considerazioni sull'integrabilità e sulle potenzialità applicative del vetromattone integrato con DSC per la realizzazione di involucri edilizi traslucidi, colorati e sostenibili.

ABSTRACT_ENG - *The glass block is a well-known building product, which has been widely employed for the construction of spatial dividers and building envelopes, both in modern and contemporary architecture. The necessity to optimize its energy performance according to the stricter and stricter energy efficiency regulations, as well as to make it more competitive is driving several efforts for the optimization of its thermal insulation, solar and optical properties, but also for the optimization of conventional "wet" assembly systems for both internal and external installations, based on the use of concrete.*

In the light of these considerations and starting from the evaluations made in the first part of the thesis, a novel, multifunctional and translucent building component for BIPV is introduced and detailedly described. This component, developed at the Department of Architecture of the University of Palermo, is a precast, dry-assembled and pre-stressed panel made of innovative glass blocks, optimized as regards their thermal insulation and integrated with third-generation Dye-sensitized Solar Cells (DSC). In this chapter, four patented configurations of DSC-integrated glass blocks are detailedly described, basically representing all possible positions of the DSC module within the glass block. The studies conducted at the University of Palermo for the technological definition of the novel dry-assembly system, with supporting elements in moulded plastic and load-bearing structure made of pre-stressed steel bars, are also introduced here and discussed in detail.

A brief literature study regarding the use of semi-transparent PV elements for the construction of energy-saving and producing building envelopes is also provided, along with a brief outline of challenges and opportunities regarding the use of colour in translucent building skins. In this context, some considerations regarding the applicability potential of the DSC-integrated glass block components for the construction of translucent, colorful and sustainable building envelopes are eventually made.

4.1. Introduction

The first part of this thesis has underlined the great attention addressed by the scientific and technical communities towards the theme of the integration of photovoltaics in buildings and, at the same time, the importance of the technical progress in the BIPV industry for the definition of new solutions and the upgrade of existing ones.

In particular, the architectural integration of semi-transparent photovoltaic (also referred to with the acronym, STPV) products as technical elements of glazed façades and roofs is widely acknowledged as a very interesting option for the construction of sustainable building envelopes. Indeed, when such solutions are appropriately incorporated into building design, they not only generate clean electricity, but also enable the optimization of building energy performance thanks to the daylight modulation and thermal insulation provided. These characteristics turn out to be even more relevant if we consider that a large amount of building envelopes nowadays are characterized by window glazing and that ordinary glass generates high energy consumption at the operational stage due to high solar heat gains (Morini et al., 2015). As it is possible to deduct from the analysis of the state of the art of BIPV industry offering and from the study of built examples, they need to be carefully thought according to the requirements of each installation, in order to provide the best balance among energy-related, constructional, architectural and economic requirements.

On the one hand, manufacturers of BIPV systems — and, more in general, of building products — are called to provide their solutions with performance levels compliant with the stricter and stricter building regulations and with the widest customizability (in terms of appearance, energy performance, and so on…); on the other hand, building planners are engaged in the definition of the product performance range that is more adapted to the characteristics of each building, its location and its functions.

It has been widely underlined how, among all photovoltaic technologies, 3rd generation Dye-sensitized Solar Cells (DSCs) seem particularly promising for these kinds of installation. This is mainly because of the wide range of transparency and coloration obtainable as well as the bifacial configuration of DSC modules integrated on transparent substrates (which can convert electricity from both external and internal environments). As also stated by Desilvestro et al. (2010) «*…the optical transparency and coloration of DSCs can be readily varied in virtually unlimited combinations through the adjustment of the thickness and type of* TiO_2 *film as well as the nature of the dye, without requiring any additional manufacturing hardware…*» (p. 238). Several attempts have been made both at optimizing the transparency and electric performance of DSCs for BIPV roof and façades (Halme et al., 2012) and for the development of stable and efficient DSC products for architectural glazing applications (Hinsch et al., 2011). Such attempts bear witness to the interest expressed in the BIPV sector by companies and research centers working with DSC technology.

This thesis is inserted in a wider work of research, carried out at the Department of Architecture of the University of Palermo, aimed at the energy performance optimization of light-capturing elements of the building envelope[1].

In particular, the research focused on the energy performance optimization and technological upgrade of the glass block, in order to allow for its use in the construction of translucent and sustainable building envelopes.

The second part of this thesis regards the technological definition and energy optimization of a novel component for the construction of translucent, energy-saving and producing building envelopes: namely, a multifunctional panel made of glass blocks integrated with third-generation DSCs (Corrao, Morini & Pastore, 2013). The development and commercialization of this building component is the main objective of the technological start-up company and spin-off of the University of Palermo *SBskin. Smart Building Skin s.r.l.*[2].

4.2. The Glass Block

As shown by contemporary architectural trends, nowadays glass turns out to be diffusely used for the construction of transparent or translucent envelopes for both new and retrofitted buildings. Nevertheless, glazed surfaces represent an awkward aspect among the building envelope components, since their thermal resistance is generally lower than the opaque ones. This is essentially due to the energy transmission occurring through glazed surfaces, possibly causing – if not accurately controlled – excessive heat loss during winter and indoor overheating during summer.

The glass block is a well-known building product widely used for the construction of spatial dividers as well as for building envelopes. It is formed by two glass shells, obtained by pressing a drop of fused glass on a stamp and joined together through hot or cold gluing processes, creating an internal cavity. The glass blocks allow light to pass through in different percentages, depending on the colour of the glass and on the finishing of the glass shell faces. Moreover, it is a building product provided with great variety of possible geometries and finishing. For example, for the Maison Hermés in Tokyo (2003) by Renzo Piano (Photo 1), approximately 13,000 customized glass blocks were used, specifically designed

Photo 1 - Maison Hermés, Tokyo, Renzo Piano Building Workshop, 2003

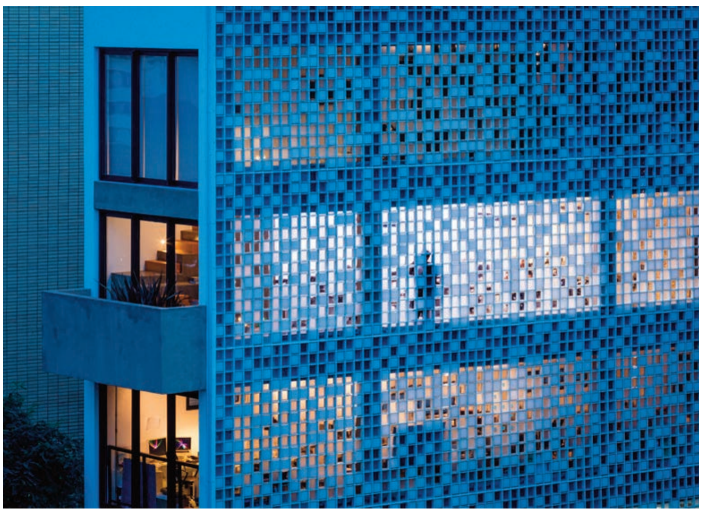


Photo 2 - Leitão_653 building, Tryptique, São Paulo, 2013: view of the “chequerboard” glass block façade

– as regards both dimensions, appearance and finishing treatments – by the Italian architect and tailor-made by the company SEVES[3]. The glass block may be preferred to traditional flat glass for its performance in terms of acoustic insulation and fire-resistance due to the presence of a thick air cavity as well as for its peculiar translucency and modularity (two aspects that have already been widely investigated, through plenty of examples, in this work due to their relevant presence in the field of architecturally integrated photovoltaics). In this sense, the 2013 project by Tryptique named Leitão_653 may represent an emblematic example: this building, thought for creative studios in São Paulo, has an entire façade cladded with a "chequerboard" of glass blocks, in three different degrees of transparency and disposed according to an irregular pattern. This allows for suggestive light effects from the outdoor to the indoor environment and vice versa (Photo 2).

Standard glass block thermal performance is still significantly lower than that of opaque claddings and this is mostly caused by the heat transmission occurring across the glazed surfaces, causing a heat loss in winter and heat gain in summer. Because of those reasons, several attempts have been made to improve glass block energy performance in order to make it compliant with the stricter and stricter regulations as regards the energy performance of the building sector and able to guarantee high levels of indoor thermal and visual comfort.

For example, the glass block manufacturing company SEVES has come out with the "Energy Saving Glass Block", characterized by the presence of a low-emissive glass sheet between the two glass shells and of argon inside the cavity of the product, in order to improve the thermal transmittance (U value) of the product[4] and allow for its use, as technical element of the building envelope, also in countries where low limits in terms of U value have been established. Nevertheless, in several countries, the stricter and stricter restriction are limiting the applicability of this building product as technical element of the building envelope.

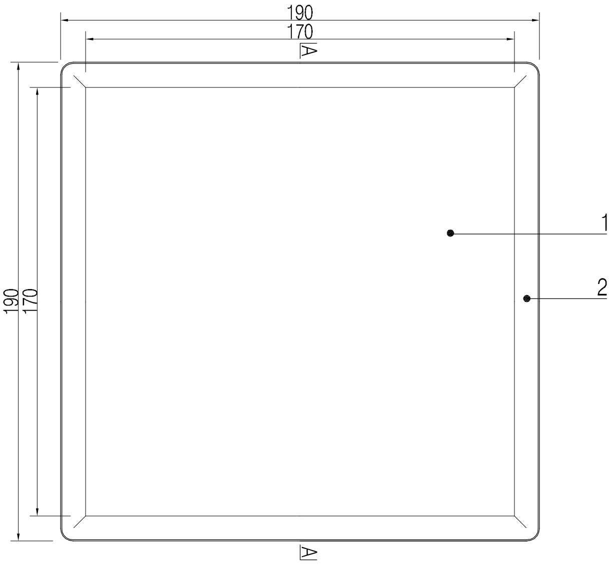
Glass block is characterized by high solar gain and light transmission values[5]. In some applications, the use of this product for the construction of transparent or translucent building envelopes — in absence of other measures for the reduction of solar gain and light transmission — may origin thermal and visual discomfort inside the buildings. For example, in case of high levels of solar radiation, Fanchiotti et al. (1999) suggest to use colored and/or diffusing glass blocks for application in the building envelope in order to avoid possible phenomena of visual discomfort.

As in all glazed elements of building envelopes, the aspects regarding solar gain and light transmission values should be carefully studied according to the characteristics of each project. These could actually represent a significant issue especially in geographical areas characterized by a warm climate (e.g. the Mediterranean Basin), due to the high temperatures and solar radiation levels during the whole year. Measures to optimize glass block performance, which take into account this aspect, need to be taken too, in order to enable glass block to respond to diversified requirements also in terms of daylighting and solar gain.

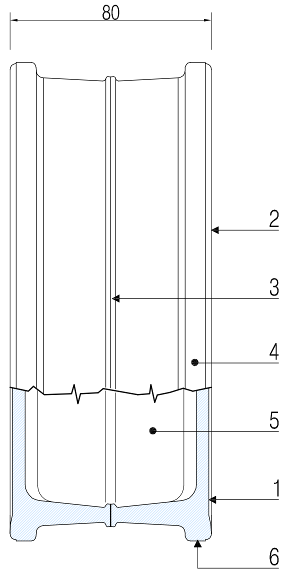
The study and optimization of the energy performance of the glass block moves from the above considerations and is described in detail in the following pages.

4.2.1. Reference “standard” Glass Block

The standard glass block that is used as reference in the present work is the *Pegasus Q19* manufactured by SEVES. The two glass shells that form it are joined by means of a hot-gluing process and the high temperatures (approximately 900° C) reached in this process allow for the drying of the air in the cavity, which helps to avoid condensation inside the product[6]. Pegasus Q19 is characterized by a square surface with sides of 190mm and 80mm thickness (Figure 4.1). The thickness of the glass shells in the central part of the product, corresponding to the so-called “vision area” of the product, is equal to 5mm and thus the thickness of the internal cavity is 70 mm.

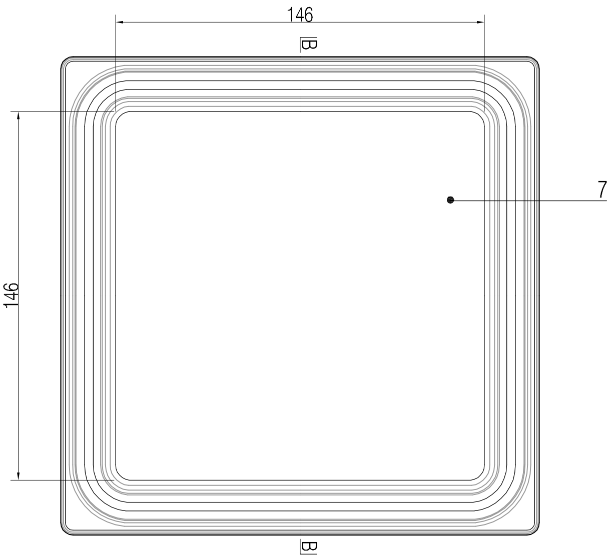


Front view of the glass block



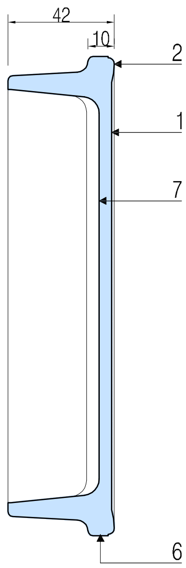
Side view/Cross section AA

Photo 3 - Different glass block types by SEVES



SCALE 1.3

Rear view of a glass shell



Glass shell cross section BB

LEGEND

1 Outer surface

2 Glazed border

3 Welding line

4 Glass shell

5 Cavity

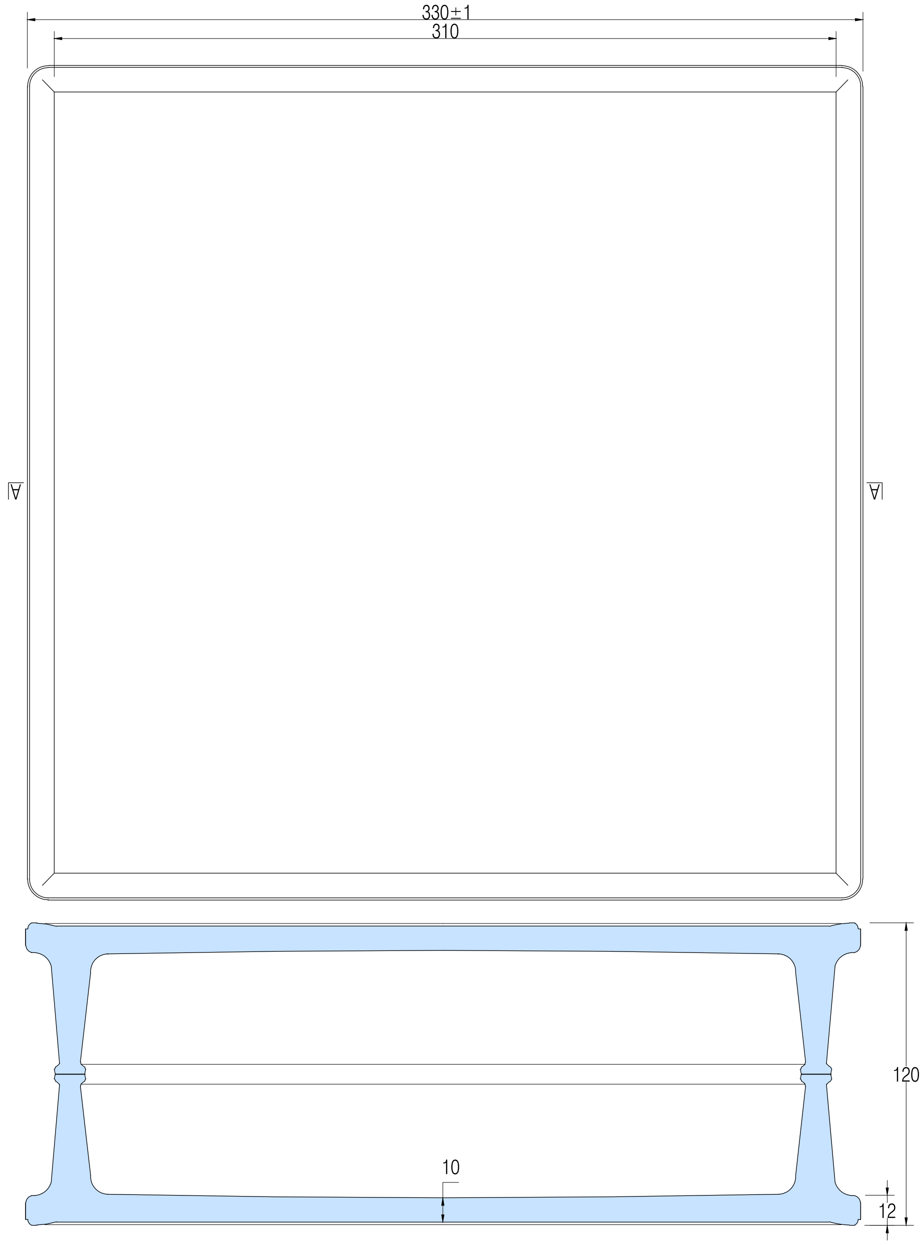
6 Side wing

7 Inner surface

Figure 4.1 - *(left) Standard* Q19 GB 190x190x80mm

Different types of glass and finishing can be used in order to modify the appearance and optical behavior of the product (see, for example, Photo 3) but, for the purpose of the analyses carried out in the present work, Neutral Q19, made of clear highly transparent glass will be accounted for.

Another glass block type has been analyzed in the present work, in order to make some comparisons with that introduced above: the *Ginza Collection Q33* by SEVES, characterized by the same shape but different dimensions, i.e. 330mm side and 120mm thickness (Figure 4.2). The thickness of the glass shells in the central part of the product is equal to 10mm and thus the thickness of the internal cavity is 100mm.



Front view and cross section AA of the Q33 glass block *SCALE 1.3*

Figure 4.2 - *(right)* *Standard* Q33 GB 330x330x120mm

4.3. Energy Performance Optimization of Glass Block

As already underlined, in the field of the research where this work is inserted, the glass block has been “modified” in order to improve its thermal insulation performance and respond to the stricter and stricter regulations that lowered the minimum acceptable U values of glazed building components and thus limited significantly its use for envelope applications.

Moreover, in order to further improve its energy performance, the glass block has also been enabled to produce clean electricity through its integration with 3rd-generation Dye-sensitized Solar Cells (DSCs). Besides the obvious advantages linked to the PV performance, the integration with DSCs could have also positive relapses in terms of visual and thermal indoor comfort conditions, since a wide range of light transmission and solar protection performance could derive from the integration of the glass block with different types of DSC devices. Clearly, such integration has also an impact on product’s appearance (in terms of colour, transparency, design).

4.3.1. Thermal Performance Optimization of Glass Block

New glass block configurations, able to notably increase product thermal and optical performance, have already been studied at the Department of Architecture of the University of Palermo, in previous works[7].

The main operations that were considered for the improvement of glass block U value are:

- the subdivision of the cavity in two or more chambers through the insertion of one or more sheets of transparent insulating material (such as glass, polycarbonate, polycarbonate+aerogel); this subdivision reduces the dimension of the cavity inside the glass block, intervening through the reduction of the convective heat transfer;
- the insertion of a “thermal belt” in plastic material (which has lower thermal conductivity than glass) between the glass shells composing the glass block, in order to reduce the part of heat transfer related to conduction. The thermal belt (Figure 4.3), to which the glass shells are cold-glued by means of a resin, is also thought for making the insertion of the sheet/s inside glass block cavity notably easier and for guaranteeing a higher mechanical tightness to the whole product;
- the evacuation of the cavity.

In the present work, other operations have been considered in order to improve further the thermal insulation of the product. For example, the insertion of a low-emissive glass sheet inside glass block cavity. Besides the benefit related to the subdivision of the cavity of the product and consequently the reduction of the convective heat transfer, the low-emissive coating cuts down the radiative part of the heat transfer. Furthermore, it has also been studied the possibility to fill the cavity of the glass block with argon, which is better insulating than dry air. The novel configurations will be detailedly described and analyzed in the following chapter.

Besides the studies — that are widely discussed and presented in the next chapter — on the effects of the thermal belt on the thermal and optical performance of the product,

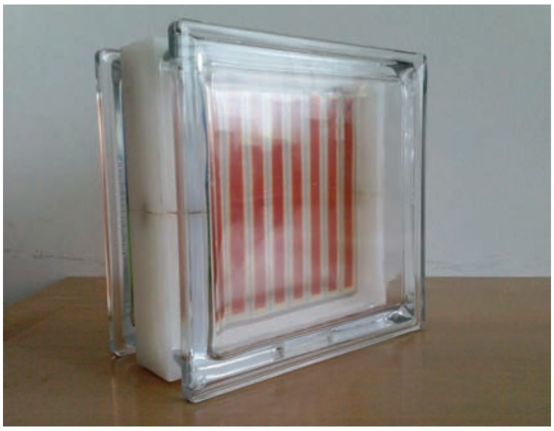


Photo 4 - Prototype of the glass block both assembled (with thermal belt and polycarbonate sheet) and disassembled

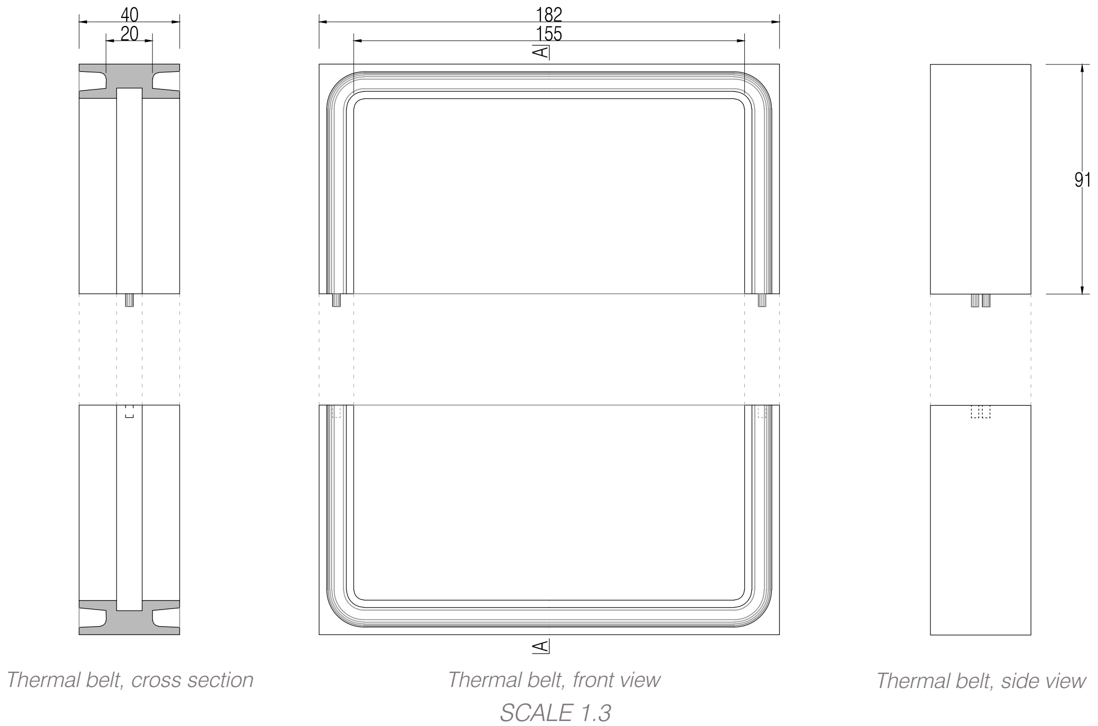


Figure 4.3 - The thermal belt, developed for assembly with Q19 glass shells

the research where this work is inserted has also been focusing on the study of the mechanical performance of the thermal belt through analytical and experimental studies made on prototypes (Photo 4) as well as on the tightness of the gluing between nylon and glass[8].

4.3.2. Integration of Glass Block with 3rd Generation Photovoltaics

In Morini (2012), four configurations — the so-called "Hypotheses" — of glass block integrated with third-generation photovoltaic cells have been deeply studied and described. These patented[9] configurations basically represent the four main modalities, through which the DSC module can be integrated glass block, i.e.: on the outer surface of the sun-exposed glass shell (with different coverage of glass block surface); on the inner surface of the sun-exposed glass shell; inside the cavity of the product (housed in the thermal belt).

These four configurations differ because of: the position of the module inside the glass block; the dimensions of the solar module; the characteristics of the glass block. As regards, in particular, the dimensions of the module, a generic thickness "t" is considered[10], while, in order to easily compare among each other DSC module dimensions in the different configurations, a specific parameter had to be defined: the *Module Area Percentage*, obtained as the ratio of the area of the DSC module integrated into the glass block (m^2) by the area of the glass block external surface (0.19x0.19 m^2 for the Q19, and 0.33x0.33 m^2 for the Q33). In the following paragraphs, a synthetic overview about the four PV-integrated glass block configurations is provided. These configurations are the starting point for the analyses on PV-integrated glass block performance that will be deeply discussed later in this work.

4.3.2.1. Configurations 1 and 1a

The Configuration 1 (Figure 4.4) consists in the integration of DSCs on the external surface (2) of one of the two glass shells (0) forming the glass block (supposedly the one exposed to the sun). It is characterized by the modification of the shape of one of the glass shells for the integration with DSCs (3). In particular, the face of the glass shell (2), where the DSCs are integrated, presents a border (1) running through all the perimeter of the external face like a frame, which can also be useful to improve the tightness of the solar device to the surface of the glass block.

The Configuration 1a (Figure 4.5) foresees the possibility of integrating (by means of a resin) in the modified glass shell, as described above, a complete DSC module (5), already manufactured. It may be positioned in the plane area of the glass shell, framed by the border.

The two configurations only differ because of one aspect: in Configuration 1, the "modified" glass block face constitutes one of the substrates of the DSC device; in Configuration 1a, a complete DSC module is integrated on the "modified" glass block face. The latter has been used for the energy performance analyses that will be described later in this chapter, because of possibly easier logistics and manufacturing process, which makes it more suitable for architectural purposes.

From now on, when referring to Configuration 1, Configuration 1a will be implicitly meant.

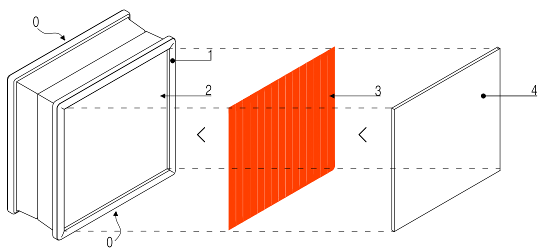


Figure 4.4 - Scheme of the Configuration 1

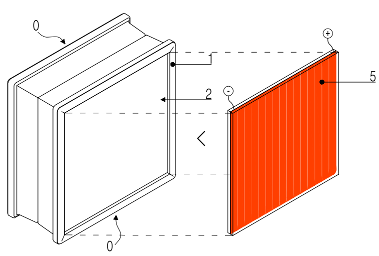
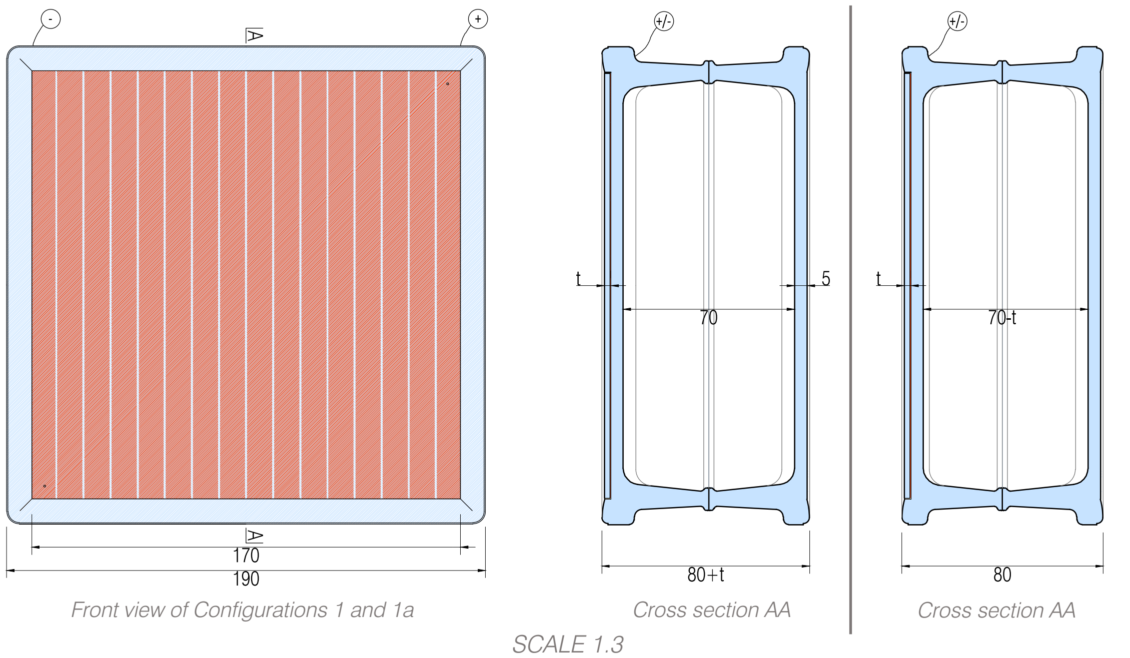


Figure 4.5 - Scheme of the Configuration 1a



	19x19	33x33
Glass Block Thickness (m)	0.080 + t[11]	0.120 + t
Module dimensions (m)	0.170	0.309
Module area (m²)	0.0289	0.0955
Module area percentage (%)	80.06%	87.68%

Figure 4.6 - Drawings of Configurations 1-1a (Q19) and table indicating main dimensions for both Q19 and Q33; *(right)* glass block integrated with PV according to Configuration 1 modified to obtain a standard 80-mm thickness

In order to maintain the thickness of the DSC-integrated glass block unvaried with regard to the standard product, the glass shell can be modified accordingly as shown in Figure 4.6, right.

4.3.2.2. Configurations 2 and 2a

The Configuration 2 (Fig. 4.7) consists in the modification of one glass shell (0) and in the integration of the DSC with the already assembled glass block, with the aim of increasing the active area for the deposition of the DSC. The entire glass shell face (1), where the solar cells are integrated, is flattened, so that it can possibly offer a complete plane area for the deposition of the solar cells (2).

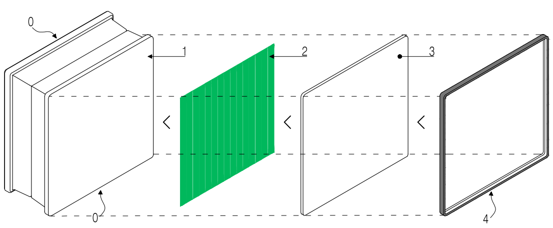


Figure 4.7 - Scheme of the Configuration 2

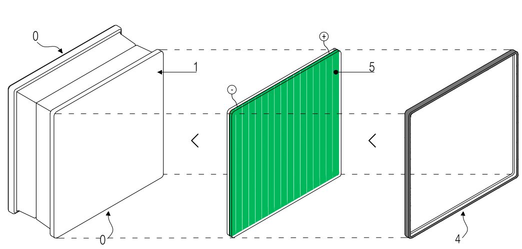
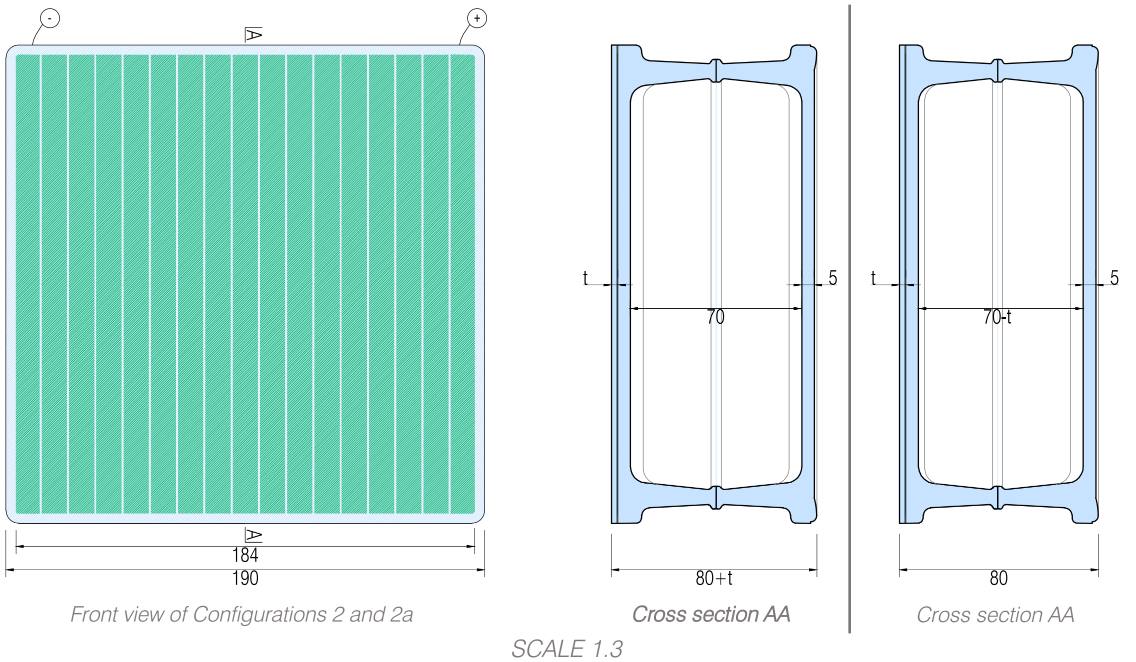


Figure 4.8 - Scheme of the Configuration 2a

The Configuration 2a (Figure 4.8) foresees the possibility of integrating in the modified face (1) of the glass shell (0), as described above, a complete DSC module (5) already manufactured. In order to improve the tightness of the solar device to the flat surface of the modified glass shell, a protection perimetrical element (4), like a gasket, could turn out necessary.

From now on, when referring to Configuration 2, Configuration 2a will be implicitly meant.

In the same way as in Configuration 1, the necessity to maintain the standard thickness of the product could require the modification of the glass shell shape (Figure 4.9, right).



	19x19	33x33
Glass Block Thickness (m)	0.080 + t	0.120 + t
Module dimensions (m)	0.184	0.321
Module area (m^2)	0.0339	0.1030
Module area percentage (%)	93.78%	94.62%

Figure 4.9 - Drawings of Configurations 2-2a (Q19) and table indicating main dimensions for both Q19 and Q33; *(right)* glass block integrated with PV according to Configuration 2 modified to obtain a standard 80-mm thickness

4.3.2.3. Configurations 3 and 3a

In Configuration 3 (Figure 4.10) the shape of the glass shell (0) is maintained: its internal planar face (1) functions as the substrate for the integration of the cells (2).

The position of the cells inside the cavity of the glass block, on the one hand, could be a great advantage in terms of durability of the solar device, which, de facto, is protected from the external environment and, consequently, from the atmospheric agents (like rain, hail, wind) as well as other mechanical or chemical agents.

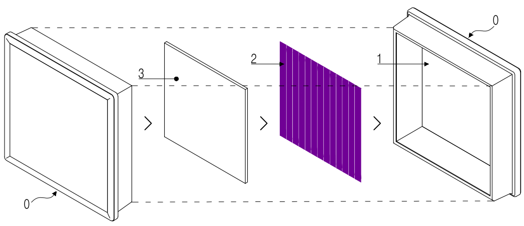


Figure 4.10 - Scheme of the Configuration 3

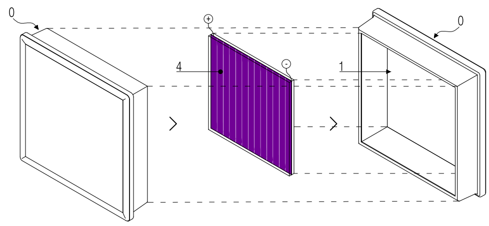
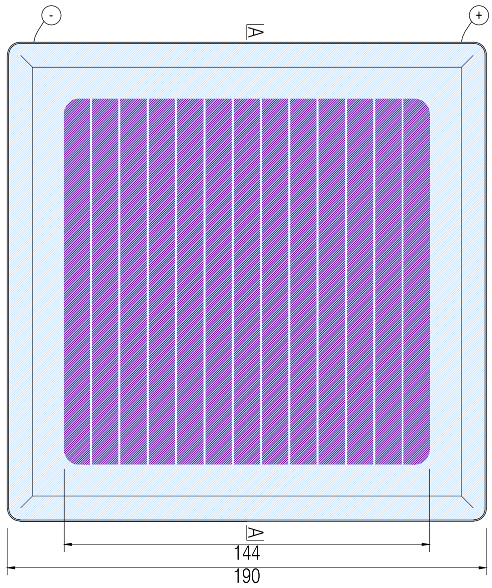
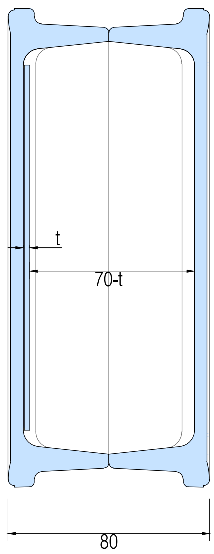


Figure 4.11 - Scheme of the Configuration 3a



Front view of Configurations 3 and 3a



Cross section AA

SCALE 1.3

	19x19	33x33
Glass Block Thickness (m)	0.080	0.120
Module dimensions (m)	0.144	0.264
Module area (m^2)	0.0207	0.0697
Module area percentage (%)	57.44%	64.00%

Figure 4.12 - Drawings of Configurations 3-3a (Q19) and table indicating main dimensions for both Q19 and Q33; *(right)* glass block integrated with PV according to Configuration 3 modified to obtain a standard 80-mm thickness

On the other hand, the deposition of cells can not happen when the glass block is assembled and, moreover, the traditional hot gluing of the two glass shells (0), with its high temperatures, would be fatal for the DSCs, so a cold assembly by means of resins must be undertaken.

The Configuration 3a (Figure 4.11) foresees the integration of a DSC module (4) already manufactured on the plane internal face (1) of the glass shells and it is the one studied in the field of the energy performance analyses executed in this work.

When referring to Configuration 3, from now on Configuration 3a will be implicitly meant.

4.3.2.4. Configuration 4

In the Configuration 4 (Figure 4.13) a DSC module (1) is inserted in the thermal belt (2), subdividing the cavity of the glass block into two chambers. The thermal belt offers the support for the DSC module and the glass shells (0) through an easy assembly. It must integrate the holes (3) for the passage of the wires for the electrical interconnection of the modules. Also in this case, the shape of the glass shells remains unchanged, unless of eventual modifications aimed at maintaining the thickness of this DSC-integrated glass block configuration equal to the standard (80 mm).

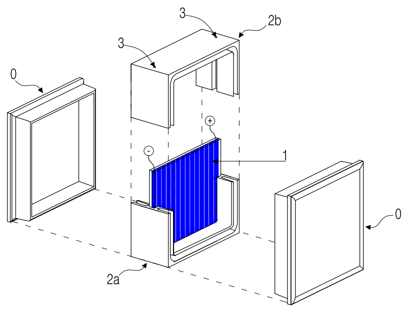
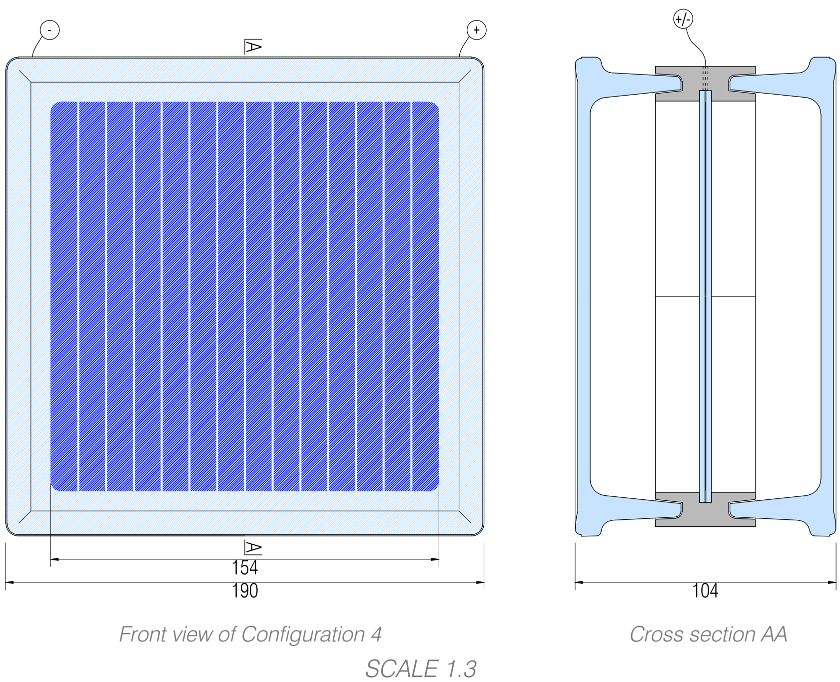


Figure 4.13 - Scheme of Configuration 4



	19x19	33x33
Glass Block Thickness (m)	0.080-0.104	0.120-0.144
Module dimensions (m)	0.154	0.275
Module area (m^2)	0.0237	0.0756
Module area percentage (%)	65.70%	69.44%

Figure 4.14 - Drawings of Configuration 4 and table indicating main dimension for both Q19 and Q33

In order to maintain the standard 80-mm thickness of the glass block, the glass shells could be reduced as will be discussed in the next chapter at paragraph 5.5.6, where the effects of this operation in terms of glass block thermal transmittance will be studied too.

4.4. Dry-assembled Glass Block Panels for the Building Envelope

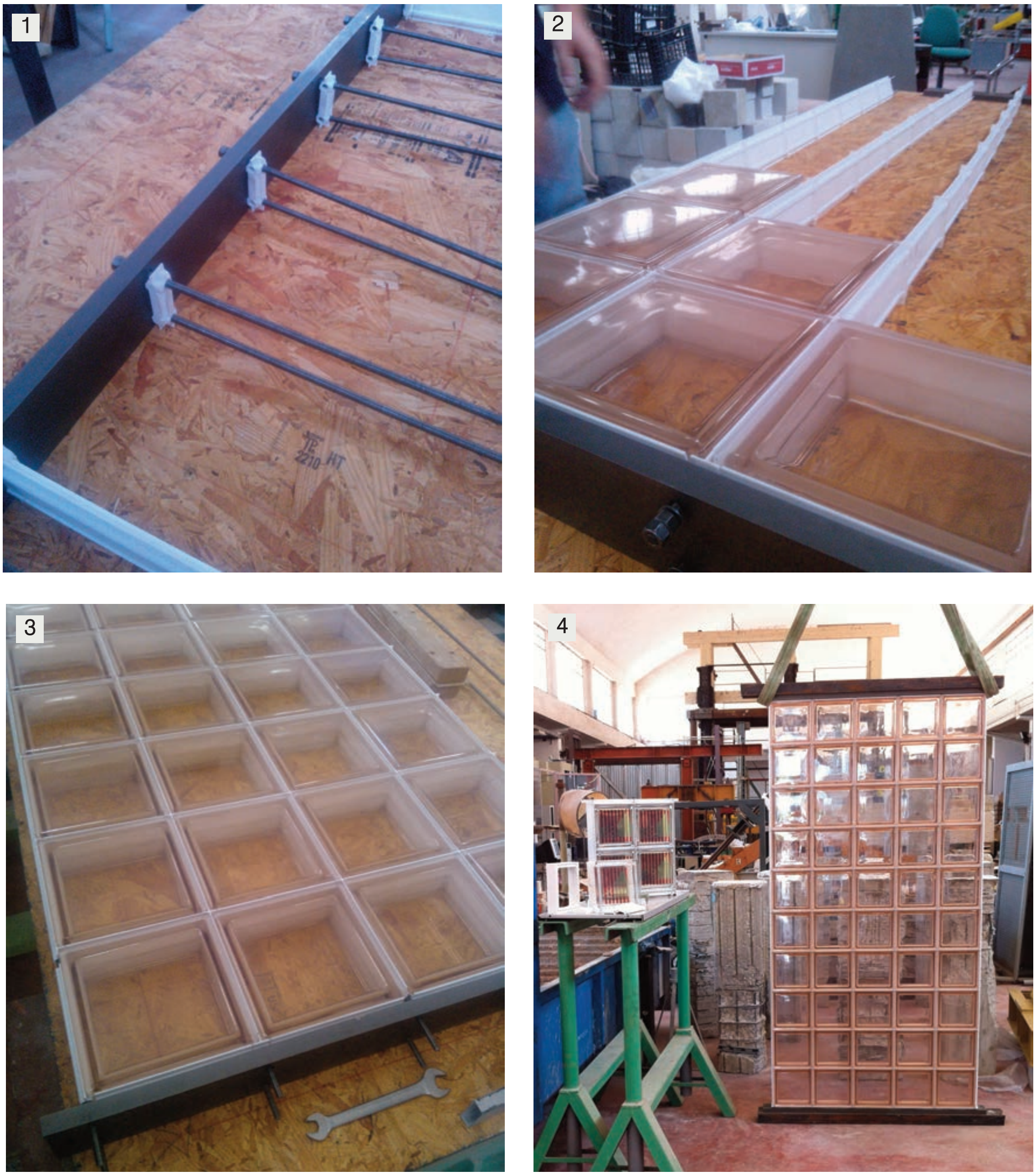
In the field of the research where this work is inserted, a system for the “dry assembly” of the glass blocks (either standard, thermally optimized or PV-integrated) into panels has been developed and patented as well (Corrao, Morini & Pastore 2013).

Glass block walls have traditionally been installed as building components filling the spaces between the structural elements. Steel bars, positioned in the cavities between the glass blocks, are used to stiffen the panels and then mortar is put in the same cavities where the steel bars are placed in order to joint all the elements together. This type of “wet assembly” system enables the construction of glass block walls (either made of precast panels or not) with joints that are generally more than 5-10 mm thick, often depending also on the ability of the installers. Moreover, this system does not enable translucent panels to immediately achieve adequate levels of mechanical resistance because of the mortar setting time, requiring, at the same time, the presence of a horizontal laying base where to built the glass block walls (which turns out incompatible with curtain wall construction).

For the construction of translucent envelopes even in high-rise buildings, it is necessary to overcome the limits due to the traditional assembly system that has been used so far to build panels for external use. Actually, in high-rise buildings — quite often characterized by glazed curtain wall solutions, as shown by contemporary architectural trends — the problems related to the action of horizontal forces, such as wind and earthquake, must be taken into account, as well as the necessity to speed up the construction of the building envelope, in order to reduce the building costs.

For all the above reasons, a "dry assembly” system for glass blocks (illustrated in Photo 5 and in Figures 4.15-16) has been developed, enabling the attainment of precast and prestressed translucent panels, that are able to better respond to horizontal forces and can be quite easily fixed by means of mechanical connections to the load-bearing structure of buildings. These dry-assembled glass block panels are characterized by a supporting structure consisting of plastic[12] moulded profiles provided with holes for the passage of stiffening steel bars that are positioned along the prevalent dimension of the panel, running lengthwise through the vertical profiles. The steel bars are stressed through clamping nuts in order to apply the unidirectional compressing force to the panel that is thus able to guarantee high levels of mechanical resistance against horizontal actions, which in vertical façade installations can be due, for example, to wind and earthquakes.

In case of multifunctional PV-integrated glass block panel, electric interconnections of the PV glass blocks are integrated inside the plastic profiles laid in the horizontal cavities resulting from the juxtaposition of contiguous glass blocks. The horizontal profiles, indeed, do not house any structural element and they are simply used to create the 2-mm joints between glass blocks (significantly smaller than those deriving from the use of the “wet assembly” system). This allows for the construction of almost uninterrupted glazed surfaces, an important advantage not only in aesthetic terms, but also with regards to the efficiency of the PV solutions, translating indeed into a maximized active area.



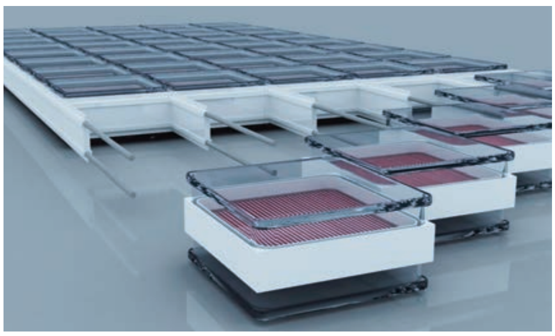
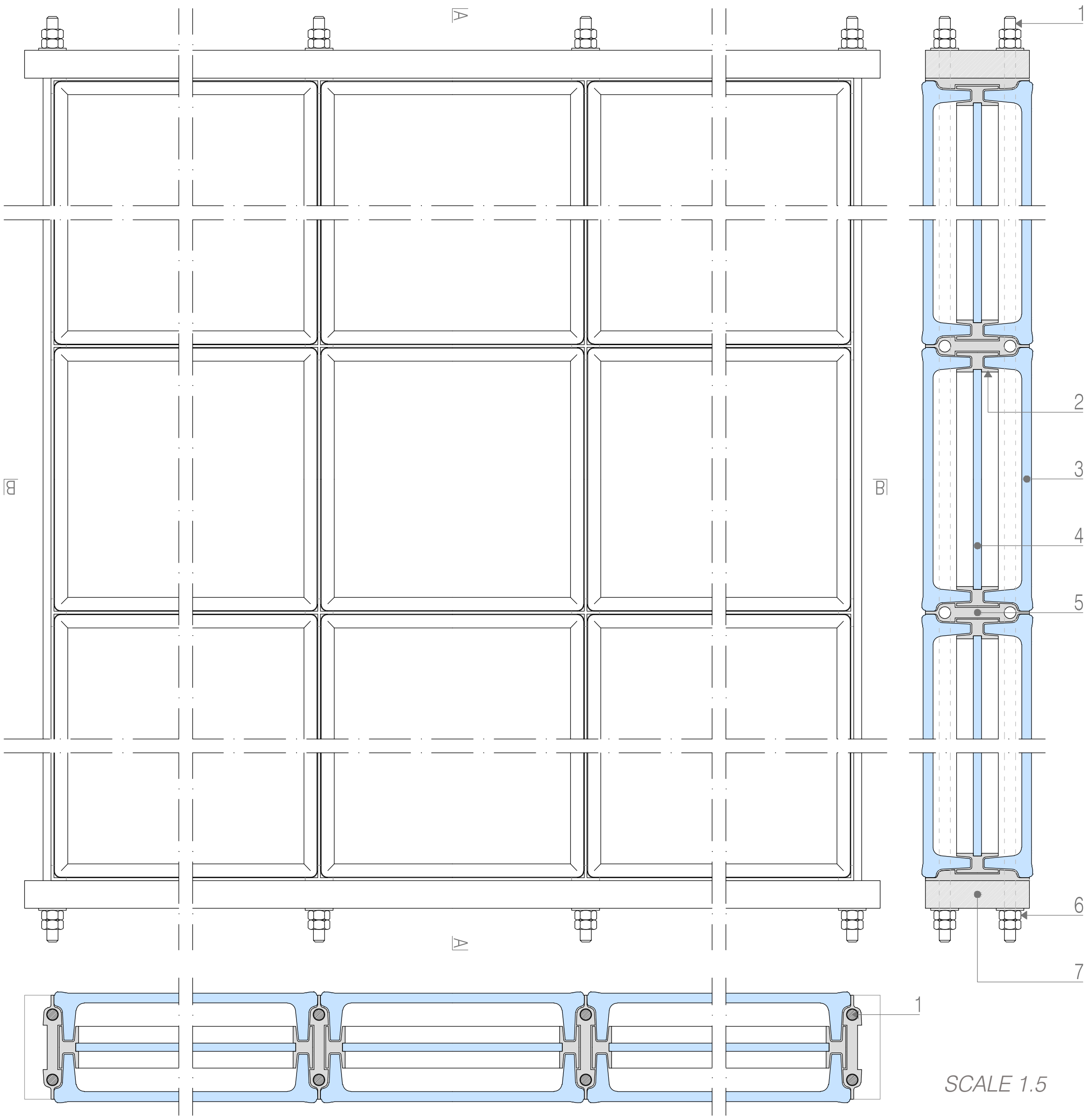


Photo 5 - Photos illustrating different phases of the assembly process of a prototype of a precast, dry-assembled panel made of “standard” glass blocks:

1) positioning of the first plastic profiles;
2) positioning of the first rows of glass blocks;
3) completion of the panel assembly, immediately before the prestressing of the bars;
4) vertical positioning of the prestressed panel;

Figure 4.15 - Render of dry-assembled panel made of PV-integrated glass blocks according to Configuration 4



LEGEND

1 - Stiffening element - Steel Bars Φ 8 mm

2 - Thermal insulation element - Plastic Thermal Belt

3 - Finishing element - Glass Shell (5-mm thick in the centre part)

4 - Thermal insulation element - Glass sheet (5-mm thick)

5 - Supporting element - Plastic Moulded Profile

6 - Clamping elements - Nuts

7 - Load-bearing element - Steel plate

Figure 4.16 - Front view, vertical and horizontal cross sections of a dry-assembled panel made of glass blocks with thermal belt

The plastic profiles have been shaped in order to adapt to different glass block configurations, either assembled with thermal belt or not, an aspect that might turn out very important for standardization purposes and for economic reasons.

In the next chapter, an analytical study regarding the possible relapses of the plastic profiles in terms of optical and thermal performance of the glass block panels is conducted, in order to evaluate possible benefits and issues. Speaking, in particular, of the possible contribution in terms of thermal insulation, it should be underlined that nylon is a material that is commonly used for the realization of the thermal break in aluminum window frames, due to its lower thermal conductivity (0.23 W/mK) than that of the metal and to its good mechanical performance. Its thermal conductivity is also lower than that of mortar, traditionally used for glass blocks assembly, hence, an improvement of overall thermal insulation performance is expected already with standard glass block. However, for a full characterization of the thermal insulation of this building component, experimental studies are necessary and these are planned for the next future.

In the field of the research where this work is inserted, this assembly system has also been studied analytically and/or experimentally as regards its mechanical performance by taking into account the two above-introduced possible dimensions of the product (190x190 mm and 330x330 mm)[13].

4.5. Semi-transparent PV: review of some analytical and experimental studies

Before proceeding with the analyses of the energy performance of DSC-integrated glass blocks, reported in the following chapter, it is of relevance to cite some of the works that in literature have analysed the impact of semi-transparent PV solutions being integrated into glazed roofs and facades on the overall building energy performance.

For example, Wong et al. (2008) conducted an analysis on the overall energy consumption of a residential building, simulated in five climate regions in Japan in order to assess the energy saving potential of the semi-transparent crystalline silicon PV panels. All essential parameters pertaining to the power generation, thermal and optical characteristics of semi-transparent crystalline silicon PV panels had previously been experimentally characterized and validated. Olivieri et al. (2014) analysed the energy saving potential of five semi-transparent PV elements based on amorphous silicon technology and characterized by different degrees of transparency over different window-to-wall ratios (WWRs). The results of the analyses, which were conducted on an office building taken as reference, were compared with a conventional glass compliant with Spanish technical standards and demonstrated that the choice of appropriate WWR and degree of transparency of the PV glazing are of great relevance to the optimization of building energy efficiency.

Most of the research conducted on semi-transparent PV building has focused primarily on first- and second- generation PV technologies. However, some studies have also investigated the potential applications of semi-transparent dye-sensitized solar cells. Kang et al. (2013), for example, evaluated the thermal and optical performance of DSC glazing by means of the WINDOW software package, using measurements on solar devices with a range of degrees of transparency and colours. Other studies have already investigated the interactions between the transparency, the efficiency of DSCs and the overall efficiency of a building when DSCs are applied as a window system under different conditions of installation, due the particular suitability of this third-generation technology for such kind of installation. For example, in Yoon et al. 2011, simulations on the energy efficiency of an office building located in Korea and equipped on its four façades with DSC-integrated windows have been performed by means of Ecotect[14] software. Different levels of visible transmittance, varying from 25-45% according to the thickness of the TiO_2 film, were considered for the analyses; the highest transparency corresponding to the lowest electrical power, and vice versa. The building simulations, taking into account both thermal, lighting, and electricity aspects, demonstrated that the best combination in terms of overall energy efficiency is not the one corresponding to the maximum photovoltaic efficiency, but rather is strictly dependant on the transmittance of the solar cells, which have important relapses on cooling and heating loads for the building. Overall, changing the transparency according to the orientation of the different façades turned out to be the best solution. Starting from the results of this paper and using the same DSC devices, Lee et al. (2014) evaluated the feasibility of window-integrated semi-transparent PV systems in different climate contexts (by referring to seven different cities around the world). A great variety of inputs were given, regarding window-to-wall ratio, DSC transparency, façade orientation, type of glazing coupled with the modules, etc. The results of the analyses, executed with the support of ESP-r[15] software, were plotted in order to define the best combinations for each climate based on the evaluated building performance.

The two above studies are useful to demonstrate the great potential of DSCs for the integration as technical elements of translucent and/or semi-transparent building envelopes: Yoon et al. (2011) even define DSCs as «*...one of the most promising photovoltaic systems for building integration...*» (p. 1899). At the same time, these works underline the importance of a systemic approach that takes into account the whole building performance and does not only focus on the maximization of PV power and thus to the highest "opaqueness" of the solar devices, not necessarily corresponding to the lowest energy consumptions.

None of these two studies takes into considerations the relapses of the different DSC-integrated window solutions analysed referring to the aesthetic and psychological effects: this is even underlined as a limitation in Lee et al. (2014). Besides the energy-related aspects, indeed, these are relevant aspects, especially as regards users' comfort, and they should be taken into account when evaluating the performance of a STPV solution. For example, Lynn et al. (2012) stated the importance of characterizing the color rendering performance of semi-transparent PV for the assessment of the visual comfort of occupants of buildings and measured it experimentally on different samples of thin-film modules. It is easily understandable how these particular aspects turn out even more relevant in third-generation PV technologies (and DSCs, in particular), whose translucent and colorful appearance can have significant effects not only on the architectural level but also on the perception of indoor spaces by building occupants. This might translate into a great opportunity in terms of design possibilities but, at the same time, must be taken into account carefully in order not to compromise the comfort conditions of the occupants of buildings.

4.6. Colored (Solar) Building Envelopes: limits and potentialities

As stated in the Preface to the Proceedings of Colour and Light in Architecture International Conference, held in Venice in 2010, «...*colour and light are fundamental to the quality of architecture, having dramatic effects on the perception of the built environment...*» (Zennaro, 2010). Color in architecture has always been exploited to convey messages and emotions as well as to define the spatial and architectural experience. In this sense, one can cite the medieval stained glasses of Gothic architecture, teaching through the representation of stories from the Bible while creating unique light effects in the naves of sacred buildings. Moving towards contemporary architecture, also the work from the Danish-Icelandic artist Olafur Eliasson called "Your Rainbow Panorama" is a perfectly suited example: this ring-like panoramic walkway, cladded in glasses in all colors of the rainbow and suspended over the roof of Aarhus Art Museum (ARoS), offers a unique 360° view of the city; glasses act as visual filters that visitors can change through their own movement (Venn, 2014), enabling an ever-changing perception of the city of Aarhus (Photo 6).

In this framework, new photovoltaic generations, and especially DSCs, possess a great added value that lies in their possibility to turn coloured and translucent glass panes into energy generators. In 2014, the first multi-colored DSC façade was completed at the SwissTech Convention Centre at the EPFL (Photo 7) by Richter Dahl Rocha and Associates. This façade project was the result of a joint collaboration of the building designers with the Swiss DSC manufacturing company Solaronix and with the artist Catherine Bolle and had an international echo, representing an important showcase for DSC technology. The peculiarity of this PV integration is the effect of the light that filters through the translucent green, orange, and red PV elements inside the hall of the building, «...*bathing it in mystical light...*» (Kaltenbach, 2015, p. 16).

Photo 6 - Your Rainbow Panorama, Olafur Eliasson, Aarhus, 2011: view of the city from the walkway

Photo 7 - SwissTech Convention Centre, Richter Dahl Rocha, 2014: view of the entrance hall

It could be underlined how, in both the above-cited examples, artists accompanied architects (and vice versa) for the realization of these works, which can be referred to as something between artistic installations and architectural façades. This was possible also given the representative functions of the two spaces: a panoramic walkway and the entrance hall of a convention centre. However, in other situations, especially speaking of work places, a translucent and coloured building envelope, be it mono-chromatic or multi-colour, might alter the perception of daylight entering the building, lead to non-optimal illumination conditions and thus generate issues in terms of users' comfort (affecting the productivity and, in some cases, even the health of workers). Therefore, besides all other aspects regarding a careful daylighting design, the evaluation of properties aimed at the assessment of human response to colours — such as color neutrality, color rendering[16] and color temperature — turn out fundamental when dealing with coloured architectural glazing. De facto, based on these properties and on the type of functions performed in the indoor spaces of a building, it could be necessary to choose one colored solution rather than others. Moreover, specific limitations to the applicability of certain products could arise along with the necessity to couple them with other subcomponents with diverse daylighting performance.

The same considerations can be directly translated to the DSC-integrated glass block presented in this work and, more in general, to the glass block, a building product that has indeed always found in colour and translucency two of its main strong points, speaking both in terms of indoor and outdoor installations.

4.7. Considerations

Since its first installations, the glass block market has been characterized by a great attention towards the variety and customizability, which are clearly important characteristics in this field. For example, the glass block company SEVES has relied significantly on these two[17], having allowed customers/designers to intervene directly and actively in glass block design and production process, by choosing a particular configuration of the product not only in terms of shapes and dimensions, but also — and especially — in terms of colour, finishing, type of glass, based on the required optical, thermal, aesthetic performance. The integration with DSC modules, that can be available in potentially unlimited combinations of colours, transparency levels and designs, might be intended as a further step towards the specialization and optimization of this product, for both outdoor and indoor applications[18].

It is true that glass blocks' three-dimensional geometry and reduced dimensions might entail higher difficulties in the manufacturing process compared the typical flat glass panes, which, thanks to their planar continuity, allow for the availability of large surfaces for the manufacturing of solar modules[19]. Nevertheless, the reduced dimensions of glass blocks could actually provide interesting advantages. First of all, the characteristic modularity of glass blocks could be exploited for the definition of larger façade drawings, according to the previously discussed principles of *pixellation* and *patterning*, which result particularly recurring in the field of BIPV industry.

In addition, in the field of PV technology and, especially, of DSCs, equal all other parameters, the smaller the dimension of modules, the higher their efficiency. Therefore, the DSC module "format" imposed by the integration with the glass block could actually represent an advantage in terms of energy production, compared to larger ones (destined for flat glazing applications) that, however, are often obtained through the interconnection of smaller devices.

In this sense, a big challenge in this project is represented by the optimization of the interconnections among modules in order to minimize the related losses as well as to facilitate the process of assembly of the DSC-integrated glass blocks into BIPV components. These aspects have already been undertaken and represent future directions of developments of this research[20].

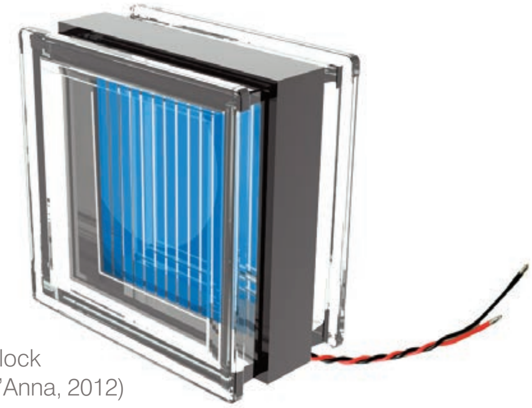


Figure 4.17 - Rendered view of the DSC-integrated glass block assembled with thermal belt according to Configuration 4 (D'Anna, 2012)

Notes

1) In particular the work was cerried out in the field of the research project financed in 2007 by the Athenaeum of Palermo (ex quota 60%), entitled: *Incremento prestazionale di componenti edilizi per la realizzazione di involucri sostenibili* and coordinated by Prof. Rossella Corrao.

2) www.sbskin.it;

3) www.sevesglassblock.com;

4) SEVES standard glass block U value is equal to 2.8 W/m²K, whereas SEVES Energy Saving Glass Block has a declared 1.5 W/m²K U value (Cf. www.sevesglassblock.com).

5) Standard glass block g-value is equal to 79.7% and light transmission is equal to 79.5%. Cf. SSV, 2008.

6) In cold-gluing manufacturing processes, several other measures can be taken in order to keep humidity out of the gas that is present inside glass block cavity and avoid the condensation phenomenon.

7) Cf. Foderà (2009); Cappello (2010); Mannino (2010).

8) Cf. Garraffa (2009); Trapani (2009); La Barbera (2015); Pollicino (2015).

9) The four configurations of DSC-integrated glass block are the object of an Italian national patent (Corrao, Morini & Pastore, 2012) and of a PCT (Corrao, Morini & Pastore, 2013), which has also been extended in Europe, US, China, Japan.

10) DSC module thickness ranges from around 4.4-6.5 mm, depending on the dimensions of the module and on its characteristics. In particular, it is mainly linked to the thickness (hardly ever below 2.2 mm) of the glazed substrates used for the deposition of the micrometrically thick active layers of the solar device.

11) The parameter *"t"* refers to the thickness of the subcomponents and/or layers added in each configuration. Hence, it can either refer to the glass that encloses the solar cells if the cells are directly deposed on the glass block (Configurations 1, 2, 3) or to the whole DSC module (Configurations 1a, 2a, 3a, 4).
12) The material chosen for the profiles, in a first stage, is Nylon PA6 (either reinforced with glass fibers or not), but the study is considering the possibility to use other kinds of materials depending on considerations that might involve type of manufacturing, processability of the material, physical characteristics, cost, and so on... These aspects are further discussed in the next chapter, by focusing especially on the thermal insulation performance.
13) Analytical simulations by means of Strauss software and experimental tests in laboratory have been carried out during the research to test the bending resistance of such dry-assembled panels, initially taking into account standard glass blocks. The maximum resistance evaluated analytical for a 1.8 m^2 dry-assembled panel, made of 50 glass block assembled with 2-mm joints, was of 447 kgf/m^2 (Garraffa, 2009 and Trapani, 2009). Laboratory tests on a real prototype confirmed the results of the previously performed simulations. The bending resistance tests were performed loading the panel by using inflatable mattresses progressively filled with water up to a 650-kgf and then progressively unloading it. The panel was prestressed by applying a twisting couple through nuts of 0.7 kgf corresponding to an axial pressing force of 446 kgf for each bar and showed an elastic behavior up to the maximum load it was exposed to. The panel performance was fully satisfying and the test was interrupted at 650 kgf although the test could proceed further (since the panel was still in the elastic phase). In particular, the maximum load tested – being the area of the panel of 1.8 m^2 – corresponds to about 360 Kgf/m^2 (Corrao et al., 2014). In La Barbera (2015) and Pollicino (2015) a dry-assembled panel made of 330x330x120mm glass blocks modified with thermal belt, has been simulated numerically and results are currently in press.
14) Cf. http://www.autodesk.it/adsk/servlet/pc/index?id=15078641&siteID=457036
15) Cf. http://www.esru.strath.ac.uk/Programs/ESP-r_overview.htm
16) This parameter will be defined and dicussed more in depth in the following chapter (paragraph 5.4.4).
17) For example, over 500 glass blocks exist in the SEVES catalogue (also see *Tailor Made* line).
18) The use of glass block for indoor application is very common and in 2011 it amounted to around 13 million pieces produced yearly, close to the 50% of the total glassblock market (source: SEVES). This research would also have an interesting impact in this sector, since big part of the energy saving could also come from indoor building applications, where glass block is a widely used product, for its aesthetic appeal and its peculiar translucency, and where DSC show a very interesting energy-harvesting potential among all PV technologies.
19) To these available surfaces, however, the portion necessary for electrical interconnections and supporting structures (i.e. frames, junction boxes, etc.) must be subtracted; in the dry-assembled multifunctional panel, made of DSC-integrated glass blocks, those elements are integrated in the moulded plastic profiles, placed in the horizontal and vertical spaces between contiguous glass blocks, hidden inside the panel thickness and resulting in only 2-mm thick joints. This could be helpful to compensate the already highlighted downsides – for example in terms of available area for photovoltaic generation – deriving from the use of glass blocks instead of flat glazing components.
20) For the sake of completeness, it is important to mention that, within this research, a line of graduation theses has been carried out entitled *"Involucri edilizi sostenibili. Impiego di materiali tecnologicamente avanzati per l'incremento prestazionale del vetromattone/Sustainable building envelopes. Enhanced materials and technologies for the energy improvement of light-capturing building elements"*, coordinated by Prof. Rossella Corrao.

In this framework, the following Master's theses in Architectural Engineering (University of Palermo) were elaborated:

- La Barbera, G. (2015). *Progetto tecnologico di un pannello in vetromattoni 33x33x12cm integrati con DSSC assemblati a secco e precompresso e caratterizzazione meccanica dei suoi sub-componenti*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. G. Giambanco; Tutor: M. Morini.
- Milia, G. (2015). *Involucri edilizi sostenibili. Riconfigurazione dell'involucro edilizio della sede dell'assessorato dell'energia a Palermo: Analisi prestazionale dello stato di fatto e di progetto* (Master's thesis), University of Palermo, Supervisor: prof. R. Corrao, Tutor: M. Morini.
- Pollicino, M. G. (2015). *Progetto tecnologico di un pannello in vetromattoni 33x33x12cm integrati con DSSC assemblati a secco e precompresso,* Supervisor: Prof. R. Corrao, Co-supervisor: Prof. G. Giambanco; Tutor: M. Morini.
- Tutone, C. (2015). *Involucri edilizi sostenibili. Riconfigurazione dell'involucro edilizio della sede dell'assessorato dell'energia a Palermo attraverso l'impiego di componenti traslucidi multifunzionali*, Supervisor: Prof. R. Corrao, Tutor: M. Morini.
- Calabrò, C. (2014). *Verifica prestazionale relativa all'integrazione di una cella DSSC nel vetromattone con "cintura termica" per la realizzazione di pannelli multifunzionali di facciata.* Supervisor: Prof. R. Corrao, Co-supervisor: S. Buscemi; Tutor: M. Morini;
- Di Maggio, M. S. (2014). *Involucri edilizi sostenibili: Analisi prestazionale tramite il software Zemax di un vetromattone integrato con celle solari di terza generazione*, Supervisor: Prof. R. Corrao, Co-supervisor: S. Buscemi; Tutor: M. Morini;
- D'Anna, D. (2012). *Sustainable Building Envelopes: DSC-integrated Glass Blocks. Performance Analyses.* Supervisor: Prof. R. Corrao, Co-supervisor: Prof. M. Beccali;
- Morini, M. (2012). *Involucri edilizi sostenibili: Integrazione di celle solari di terza generazione nel vetromattone per la realizzazione di pannelli traslucidi fotovoltaici*, Supervisor: Prof. R. Corrao.
- Cappello, D. (2010). *Simulazioni dinamiche per la valutazione delle prestazioni ottiche e termiche di nuove configurazioni del vetromattone. Intercapedine ad una camera*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. M. Beccali;
- Mannino, P., (2010) *Simulazioni dinamiche per la valutazione delle prestazioni ottiche e termiche di nuove configurazioni del vetromattone. Intercapedine a più camere*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. M. Beccali;
- Trapani, G. (2010). *Indagine teorico-sperimentale per la caratterizzazione meccanica del sistema di incollaggio a freddo finalizzato alla riduzione del valore di trasmittanza del vetromattone, Prove di laboratorio*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. G. Giambanco.
- Garraffa, A. (2010). *Indagine teorico-sperimentale per la caratterizzazione meccanica del sistema di incollaggio a freddo finalizzato alla riduzione del valore di trasmittanza del vetromattone, Simulazioni numeriche*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. G. Giambanco.
- Foderà, C. (2009). *Analisi delle problematiche connesse all'isolamento termico degli involucri in vetromattone e valutazione sperimentale di nuovi sistemi di posa in opera*, Supervisor: Prof. R. Corrao, Co-supervisor: Prof. G. Giambanco.
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Photo References

Photo 1 - Philip Denancé (www.rpbw.com);

Photo 2 - Pedro Kok (www.dezeen.com);

Photo 3 - SEVES s.p.a. (www.sevesglassblock.com);

Photo 4 - Photos of the author;

Photo 5 - Photos of the author;

Photo 6 - Manuela Oddo;

Photo 7 - FG+SG fotografie de architectura (www.detail-online.com).

CHAPTER 5
Multi-software Energy Performance Analyses of DSC-integrated Glass Blocks
Analisi multi-software delle prestazioni energetiche dei vetromattoni integrati con DSC

ABSTRACT_ITA - *L'obiettivo di questo capitolo è illustrare i risultati delle analisi prestazionali condotte su una serie di configurazioni del vetromattone, ottimizzato per quanto riguarda l'isolamento termico e integrato con celle solari di terza generazione (Dye-sensitized Solar Cells, DSC). Le analisi prendono in esame le performance termiche, ottiche ed elettriche attraverso l'utilizzo di tre software (COMSOL Multiphysics, WINDOW, Zemax), grazie ai quali è stato possibile tenere conto della particolare geometria tridimensionale di questo prodotto vetrario.*

In prima istanza, è stata calcolata, con il supporto di COMSOL Multiphysics, la trasmittanza termica di 63 configurazioni innovative del prodotto, ottimizzate in termini di isolamento termico. Tali analisi hanno dimostrato la possibilità di incrementare le prestazioni del prodotto fino a ottenere valori di trasmittanza termica molto efficienti che ne permetterebbero l'impiego per la realizzazione di involucri edilizi anche in contesti in cui le più recenti normative in materia di risparmio energetico hanno imposto limiti sempre più stringenti per quanto riguarda le prestazioni di isolamento termico dei componenti edilizi.

Successivamente, le quattro configurazioni di vetromattone integrato con DSC, presentate nel capitolo precedente, sono state analizzate nel dettaglio al fine di valutare, per ciascuna, i principali parametri (termici, ottici, ed elettrici) che ne definiscono le performance energetiche, delineandone vantaggi e problematiche. Le analisi hanno preso in cosiderazione diversi moduli in termini di colore, trasparenza ed efficienza.

Infine, sono state analizzate le prestazioni ottiche e termiche di alcune nuove configurazioni, ottimizzate a partire dai risultati appena ottenuti, al fine di fare ulteriori considerazioni in merito all'applicabilità della soluzione proposta per la costruzione di involucri edilizi sostenibili, in grado di produrre energia, ma anche — se adeguatamente "progettati" — di contribuire alla riduzione dei consumi energetici degli edifici.

Abstract_ENG - *The aim of this chapter is to illustrate the results of the performance analyses conducted on different glass block configurations optimized as for the thermal insulation performance and integrated with third-generation Dye-sensitized Solar Cell (DSC) modules. The analyses take into account the thermal, optical and electrical performance by using three different softwares (COMSOL Multiphysics, WINDOW, Zemax), also enabling to take into consideration the peculiar three-dimensional geometry of this glazed product.*

In a first phase, through the use of COMSOL, the thermal transmittance of 63 innovative glass block configurations, optimized as for the thermal transmittance (U value), was analyzed. These analyses demonstrated the possibility of increasing the thermal insulation performance of the product up to very efficient U values, in order to enable its building envelope integration even in climate contexts where the most recent energy performance regulations have imposed stricter and stricter thermal transmittance limits for building elements.

In a second phase, the four PV-integrated configurations that were introduced in the previous chapter, have been analyzed in order to assess main performance indicators (thermal, optical and electrical) and to delineate main advantages and disadvantages of each configuration. Analyses were run — and can be easily replicated — by using different DSC modules, characterized by different colors, values of transparency and efficiency.

Finally, some new configurations, optimized in the light of the previous results, were individuated and analyzed (as for the optical and thermal performance), in order to make further considerations about the applicability of the analyzed building solution for the construction of energy-saving and generating building envelopes.

5.1. Introduction and Objectives

This chapter illustrates the results of the energy performance analyses carried out on different glass block configurations optimized as for the thermal performance and integrated with third-generation dye-sensitized solar cell modules.

The objectives of these analyses are:

- to assess the energy performance of different glass block configurations proposed;
- to define a methodology for an accurate energy performance assessment of the PV-integrated glass blocks, to be validated experimentally;
- to define some optimum combinations according to the different needs of active building façades and requirements related to diversified climate contexts.

5.2. Analyses of DSC-integrated Glass Blocks Energy Performance: methodology

For the analyses, different softwares for the energy performance simulation were used:

- COMSOL Multiphysics® (COMSOL Inc., 2013);
- WINDOW (LBNL, 2014);
- Zemax (Radiant Zemax LLC, 2009);

COMSOL Multiphysics is a «...*general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems...*»[1]. It was used for a detailed calculation of the thermal transmittance (U value) of different glass block configurations, resuming a previous work (Cappello et al., 2011) that regarded exclusively some novel thermally optimized configurations and updating it with new results obtained on both PV-integrated and/or thermally optimized glass block configurations.

WINDOW is a software for the analysis of thermal and optical performance of glazing, developed at Lawrence Berkeley National Laboratory (LBNL). It was used for the evaluation of thermal and optical performance of PV-integrated glass blocks. The specific properties calculated, which will be deeply discussed in the following paragraphs, are mainly related to the solar and luminous performance of the PV-integrated glass blocks: the total solar energy transmittance (Solar Heat Gain Coefficient, SHGC or g-value), the solar and visible Transmittance (T_{sol} and T_v). The software also provided the temperature distribution on each of the layers that compose the glazing system and allowed some considerations on PV production[2].

Zemax is an optical design software, which simulates the propagation of rays through an optical system. It was used to perform deeper optical analyses on three-dimensional models of the different DSC-integrated glass block configurations and to evaluate the electric power related to each of the four previously introduced configurations (Corrao et al., 2013).

In a first phase, the analyses have been made by considering a specific DSC device deeply described in literature, to be integrated into the glass block according to the four patented configurations already discussed, in order to individuate advantages and disadvantages as well as to assess their thermal, optical and electrical performance. By integrating the results of the three software, it was possible to take into account glass block particular geometry.

After having understood the whole product performance, the analyses in WINDOW were replicated by using other DSC modules (whose detailed spectral data were available), characterized by different colors, values of transparency and efficiency.

Finally, some new configurations, optimized in the light of the previous results, were selected and analyzed by means of WINDOW software. These analyses can easily be replicated by changing input data related to DSC module characteristics (optical, thermal, electrical), active area as well as to glass block characteristics (dimension, shape, presence of other subcomponents, etc.).

5.3. Reference Standards for the Thermal and Optical Performance Evaluation

For the evaluation of glass block thermal and optical performance, there is no predisposed standard regulation. The standards that were used as main reference for the analyses are those specifically developed for flat glass, as also indicated in glass block commercial and technical guides as well as in test reports[3]:

- EN 673:2011, *Glass in building - Determination of Thermal Transmittance - Calculation Method*;
- EN 410:1998, *Glass in building - Determination of luminous and solar characteristics of glazing*.

It is also important to note that the above introduced standards are also indicated in prEN 50583-1:2014 and prEN 50583-2: 2014, entitled *Photovoltaics in buildings - BIPV modules,* as reference for the determination of the thermal characteristics (EN 673) and for the calculation of light and solar energy characteristics (EN 410) for BIPV products, containing one or more glass panes (either sloped or vertically mounted) as the product proposed.

In addition, the following standards were also used as reference:

- NFRC 100-2010, *Procedure for Determining Fenestration Product U-factors,* National Fenestration Rating Council, Inc., Silver Spring (USA).
- ISO 15099:2003, *Thermal performance of windows, doors and shading devices - Detailed calculations*.

5.4. Performance Indicators

The main indices used for the evaluation of the energy performance of glazed systems, as also stated in the International Standard *ISO 15099:2003,* are:

- the Thermal Transmittance (or U value);
- the Total Solar Energy Transmittance (or SHGC, g value);
- the Visible Light Transmittance (T_v).

Thus, window products performance is evaluated taking into account both the “dark” or “night-time” thermal transmittance (accounted without considering the effects of solar radiation) and the total solar energy transmittance, in order to characterize two opposite environmental conditions (extreme winter and summer).

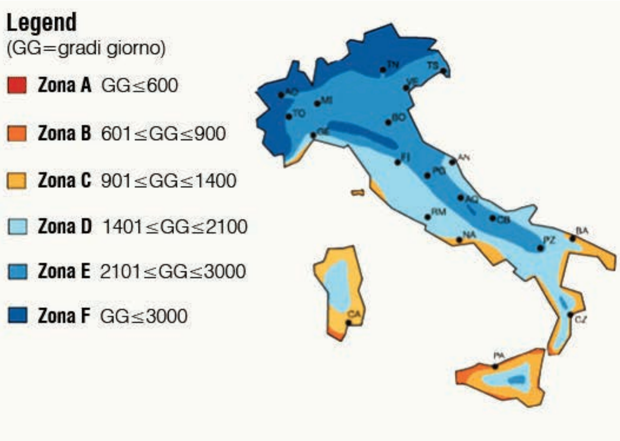
In this specific analysis, some considerations will also involve the color rendering performance (expressed by the Colour Rendering Index) of the examined product when integrated with the dye-sensitized solar module: de facto, one of the main characteristics of the solar technology is the variety of colour and transparency values, leading to a great variety in terms of daylighting performance, which needs to be understood as well.

5.4.1. The Thermal Transmittance (or U value)

According to EN 673:2011, the U value — also called U factor — is «*…the steady-state density of heat transfer rate per temperature difference between the environmental temperatures on each side…*». It is expressed in W/m²K and represents the amount of heat (W) that passes through a unit area (m²) of given building product, because of a temperature difference of 1 K between the inside and outside environment. It represents the benchmark for comparing the thermal insulation of building products and takes into account both the conductive, convective and radiative[4] heat transfer.

As it is possible to deduct from its definition, the thermal transmittance is a parameter that does not account for the effects of solar radiation striking the surface of the product (i.e., in the case of PV-integrated glass block, when the module is not functioning). Such effects are instead accounted for in the evaluation of the total solar energy transmittance. The lower the U value, the lower the rate of heat flow through the product and, consequently, the better the thermal insulation. Lower U values are required for building envelope in colder climates in order to reduce the energy consumption related to heating systems. However, improving the U value of a glazing and, in general, of building envelope materials might also have positive relapses also in terms of summer performance of a building and, consequently, for the reduction of cooling systems consumption.

If we look at the Italian Context, the Legislative Decree 311/2006 provided stricter thermal transmittance limits for glazing and window components, according to the climate zone defined as in DPR 412/93, based on a parameter called “gradi giorno”[5] (Table 5.1).



Climate Zone	U Value Glazing (W/m²K)	U Value Window (W/m²K)
A	3.7	4.6
B	2.7	3.0
C	2.1	2.6
D	1.9	2.4
E	1.7	2.2
F	1.3	2.0

Table 5.1 - Map of Italian Climate Zones according to DPR 412/93 and list of thermal transmittance limit established for glazing and window systems according to D.Lgs 311/2006 for each zone

In other countries, the transmittance limits are even more restrictive: for example, in Switzerland, the U value of a glazing (corresponding to the center of the glazing U value, not accounting for edge effects) can not be higher than 1.3 W/m^2K; the limit for the U value of a window, including both frame and glazing, is instead 1.6 W/m^2K[6].

5.4.2. The Total Solar Energy Transmittance (g value or SHGC)

Solar heat gain through glazing elements of the building envelope is a significant factor in determining the cooling load of buildings. The total solar energy transmittance (or solar factor) through transparent and translucent materials is equal to the solar heat gain that is transmitted directly through the material, plus the solar heat that is absorbed by the material and then re-emitted into the enclosed space.

It is defined, in EN 410/1998, as the «*…sum of the direct transmittance* τ_e *and the secondary heat transfer factor* q_i *of the glazing towards the inside, the latter resulting from heat transfer by convection and longwave IR-radiation of that part of the incident solar radiation, which has been absorbed by the glazing…*» (p.9). It is synthetically indicated as g value or with the acronym SHGC (i.e. Solar Heat Gain Coefficient).

It is expressed by the following formula:

$$g = \tau_e + q_i \quad [1]$$

As shown in Figure 5.1, the incident solar flux can be divided into three parts:

- the transmitted part, $\tau_e \varphi_e$;
- the reflected part, $\rho_e \varphi_e$;
- the absorbed part, $\alpha_e \varphi_e$;

where τ_e is the solar direct transmittance, ρ_e is the solar direct reflectance, α_e is the solar direct absorptance, all depending on the characteristics of the considered material. For the conservation of energy principle, the relationship among these quantities is expressed by the following equation:

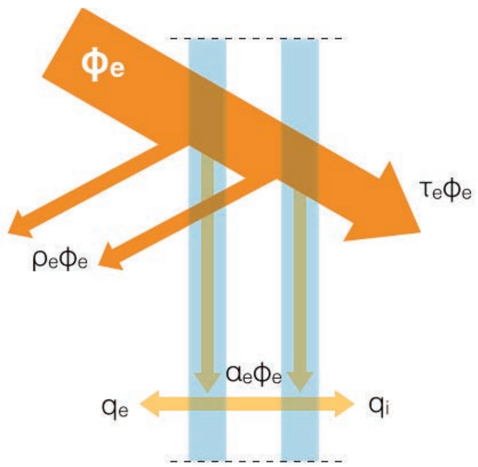


Figure 5.1 - Division of the incident radiant flux

$$\tau_e + \varrho_e + \alpha_e = 1 \quad [2]$$

The absorbed part is subsequently split into two parts, which represent the energy that is transferred towards the inside and outside, as in the following equation:

$$\alpha_e = q_i + q_e \quad [3]$$

where

- q_e is the secondary heat transfer factor towards the outside, regarding the amount of the absorbed solar energy that is conducted, convected, and/or radiated towards the outside;
- q_i is the secondary heat transfer factor towards the inside, regarding the amount of the absorbed solar energy that is conducted, convected, and/or radiated towards the inside.

The solar direct transmittance τ_e is defined as follows:

$$\tau_e = \frac{\sum_{\lambda=300nm}^{2500nm} S_\lambda \tau(\lambda) \Delta(\lambda)}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta(\lambda)} \quad [4]$$

where:

- S_λ is the relative spectral distribution;
- $\Delta\lambda$ is the wavelength interval;
- $\tau(\lambda)$ is the spectral transmittance.

It is the ratio of the transmitted solar energy flux to the incident flux.

For the calculation of the secondary internal heat transfer factor q_i it is necessary to calculate the internal and external heat transfer coefficients, respectively h_i and h_e, which depend on the position of the glazing, wind velocity, inside and outside temperature and on the temperature of the glazing surfaces. Having defined h_i and h_e, different methods are suggested by the standard EN 410, which has been taken as reference in this work, for the calculation of the secondary internal heat transfer factor towards the inside q_i, depending also on whether we are dealing with single, double or triple glasses.

The g-value is comprised between 0 and 1 and basically represents the part of the incident solar energy that is let through the glazed system as heat. The lower the g value, the lower the heat gain through a window. Clear glazing normally have high values of SHGC, around 0.86 (NSG, 2014), but significantly lower values can be reached e.g. by using spectrally selective, reflecting, and tinted glazing. In general, with all the due exceptions, glazing systems with low g-values could be preferred in warmer climates where buildings are characterized by high air-conditioning loads (e.g., in the Mediterranean Basin); conversely, glazing with high g-values could be preferred in colder climates, where passive solar heating is a good solution for an improved thermal comfort inside building during winter season. Regardless of the climate, in commercial buildings — that often generate more heat than needed from lighting, computers, machinery, and people, even on cold winter days — low SHGC are normally preferred, in order to reduce solar gain and therefore to save on cooling costs (NSG, 2014)

5.4.3. The Visible Transmittance

Another important parameter for the characterization of the properties of a glazing is the visible transmittance. It represents the amount of light (i.e. solar energy in the visible portion of the spectrum, with wavelengths ranging from 380-780 nm) that passes through a glazing material.

Similarly to the solar transmittance, it is defined as the ratio between the transmitted light flux and the incident light flux. According to the standard UNI EN 410, it can be calculated by using the following equation:

$$\tau_v = \frac{\sum_{\lambda=380nm}^{780nm} D_\lambda \, \tau(\lambda) \, V(\lambda) \, \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_\lambda \, \tau(\lambda) \, \Delta\lambda} \qquad [5]$$

where:

- D_λ is the relative spectral distribution;
- $\Delta\lambda$ is the wavelength interval;
- $\tau(\lambda)$ is the spectral transmittance;
- $V(\lambda)$ is the luminous efficiency for photopic vision defining the standard observer for photometry; this parameter is a weighting factor, accounting for the different responses of the human eye to different wavelengths.

The visible transmittance, also referred to as light transmittance, is an important parameter to be considered for the definition of the daylighting performance of any glazing. Hence, it has important relapses in terms of visual comfort for users as well as building electricity loads for artificial lighting. It theoretically ranges from 0 (opaque) to 1 (fully transparent); particularly pure glass can reach light transmittance values over 95%.

After having introduced both SHGC and visible transmittance, it is important to take into account the Light-to-Solar-Gain ratio (LSG), which indeed is defined as the ratio of these two properties:

$$LSG = \frac{Tv}{SHGC} \qquad [6]$$

The higher the LSG, the more efficient the glazing daylighting performance, SHGC being equal. Normally, to a low SHGC corresponds a low visible transmittance. Nowadays, new high-performance tinted glass and low-solar-gain low-e coatings have made it possible to reduce solar heat gain with little reduction in visible transmittance[7]. The concept of separating solar gain control and light control became very important to guarantee the optimal balance between thermal and visual comfort and this parameter turns out of great relevance in this sense.

5.4.4. Color Rendering Index

The Colour Rendering Index (CRI) of a glazing, also indicated as R_a, is a value that represents the ability of transmitted daylight through the glazing to portray a variety of colors compared to those seen under daylight without the glazing. In principle, the higher the CRI — whose maximum value possible is equal to 100 — the better; this indeed means that the perception of colors inside the building is as natural as possible and that colours are perfectly reproduced.

This value can also be referred to artificial lighting as well: in this case, the CRI expresses the conformity of a surface color with its actual appearance under the given light source.

The analytical procedure for the calculation of CRI is indicated in EN 410. Optical softwares — such as Optics (LBNL, 2013), also used in this work — integrate this procedure within their algorithms and allow for a rapid calculation of this index.

The Colour Rendering Index is of great relevance for the perception of the objects, as well as for physiological, psychological and aesthetic reasons. According to the activities performed inside building spaces — and, subsequently, the type of visual requirements, the time of permanence, and so on — different ranges of CRI are allowed.

In the standard UNI EN 12464-1:2011 the illumination requirements for internal building zones and activities are indicated. Most of the activities require a CRI higher than 80 and, in some cases, where particular visual mansions are performed, even higher than 90. Circulation spaces such as stairs, corridors, elevators can be characterized by lower CRI, but in any case higher than 40. CRI of 20 are allowed only in storage areas or machine rooms, where there are no particular visual requirements.

These are general prescriptions that are valid for workspaces and deal with the necessity to maximize visual comfort conditions during working hours. These might limit the use of coloured glass in several applications. However, the use of colored glass in architecture has been and still is a widespread practice for the innumerable ways color «...*shapes how people experience the environment visually, while as a medium, it conveys meaning, emotional moods and functional informations...*» (Buether, 2014).

5.5. Comsol Analyses of Thermal Performance

Before starting to evaluate the thermal performance of the PV-integrated glass block in different hypotheses, a previous work of U value calculation for different glass block configurations has been resumed and updated. This update was useful for adjusting some of the results and assessing thermal performance for novel glass block configurations, which have been designed in order to further improve the thermal performance of the product.

Here are illustrated the modalities of heat transfer through a glass block:

- *Conduction* between the glazed layers and the gas space, depending on the physical characteristics of the materials (and, in particular, on their thermal conductivity, λ, expressed in W/mK);
- *Convection* inside the cavity, depending on the physical properties of the gas, on the thickness of the cavity and on the temperatures on the surfaces delimiting it;
- *Radiation* inside the cavity, directly depending on the temperature and the emissivity of the surfaces delimiting it.

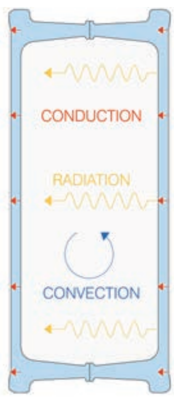


Figure 5.2 - Modalities of heat transfer inside the glass block

The input data for the materials required for the simulations were obtained from standards (e.g. EN 673:2011 for gas properties), from Comsol material libraries, and from products technical information.

Data are reported in the Table below.

Materials properties	Thermal Conductivity λ (W/mK)	Density ρ (kg/m³)	Emissivity ε
Glass	1	2500	0.837
Aerogel	0.018	160	0.86
Polycarbonate	0.12	1200	0.86
Nylon PA6	0.23	1140	-
Nylon PA6+Glass fibres	0.30	1350	-

Table 5.1 - Physical properties of the materials used for the calculations

In order to define the characteristics of the gases as regards their thermal insulation performance, it is necessary to define the specific heat capacity at constant pressure (c, expressed in J/kgK) and the dynamic viscosity (*μ* expressed in kg/ms), whereas emissivity is not required, since it is used to define the behaviour in terms of heat radiation of the surfaces of the materials that delimit the cavity/ies inside the glass block.

Furthermore, as regards vacuum, the density has been set close to 0 (since actually vacuum represents the absence of matter), whereas for its thermal conductivity, reference has been found in literature (Trushevskii & Mitina, 2008).

Data regarding the properties of the gases inside the cavity in correspondence to to the temperatures set in the simulations according to EN 673:2011, are reported as follows in Table 5.2.

Gas properties	Thermal Conductivity λ (W/mK)	Density ρ (kg/m³)	Dynamic Viscosity *μ* (kg/ms)	Specific Heat Capacity c (J/kgK)
Vacuum	0.00048	0	-	-
Air	0.02496	1.232	1.761×10^{-5}	1008
Argon	0.01684	1.699	2.164×10^{-5}	519

Table 5.2 - Physical properties of the gases inside the cavity

The software Comsol Multiphysics™ was used in both 3D and 2D environments and the “Heat Transfer Physics”, in steady-state conditions, is applied to the model.

The 2D study is executed on a CAD imported cross section of the glass block, slightly simplified in some points for accelerating software calculation process[8].

The 3D study is performed on glass block model, built in Comsol, also in this case slightly simplified in its geometry in order to accelerate software's calculation process as well as to facilitate model definition[9].

Figures 5.3 and 5.4 show the models of the "standard" glass block in 2D and 3D environments.

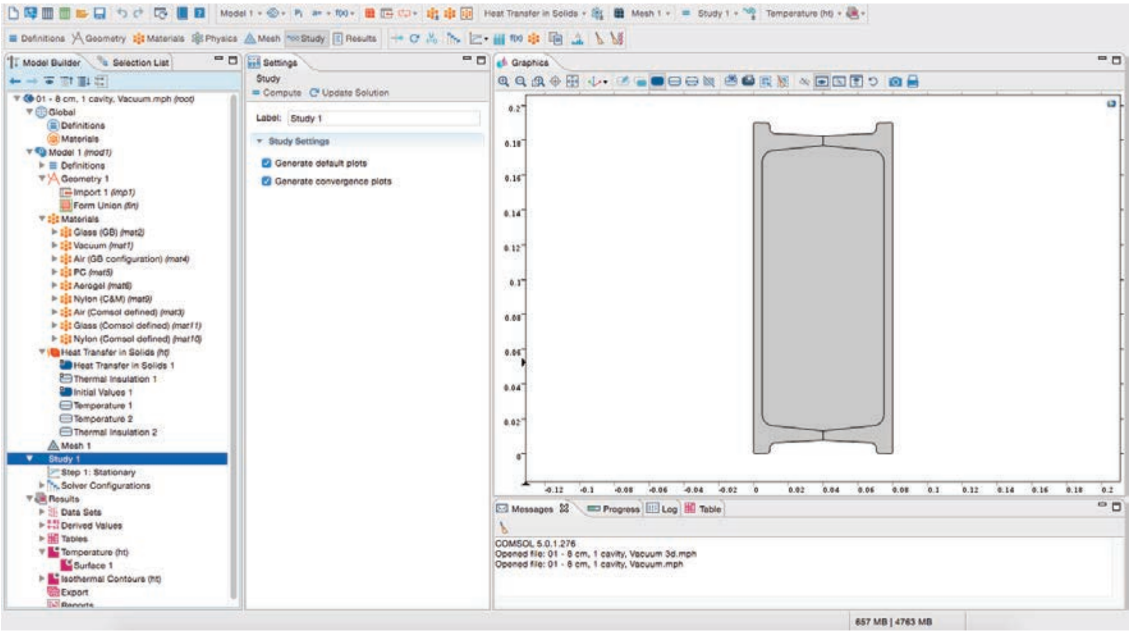


Figure 5.3 - Example of a screenshot of the software interface in 2D simulative environment

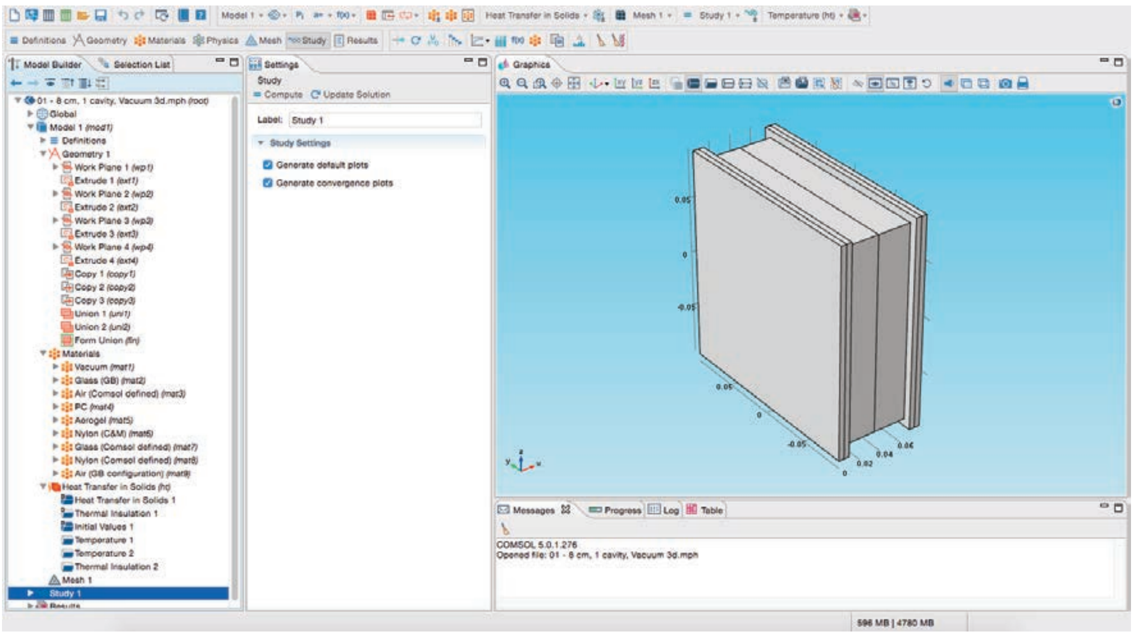


Figure 5.4 - Example of a screenshot of the software interface in 3D simulative environment

5.5.1. Methodology

The method used for calculation refers to what is indicated in the standard EN 673:2011, *Glass in building – Determination of thermal transmittance (U value) – Calculation method*[10].

The problem was analyzed imposing the temperature[11] of the faces of the glass block that are in contact with the internal and external environment:

T_e = 5 °C = 278.15 K

T_i = 20 °C = 293.15 K

The remaining lateral faces of the glass block are considered adiabatic surfaces. No radiation is striking the surface of the glass block. This situation corresponds to a winter night condition.

Since Comsol simulations for the calculation of the thermal heat transfer are executed in stationary conditions taking into account the conduction only, the heat transfer related to both radiation and convection inside the glass block is accounted through the definition of an equivalent thermal conductivity $\lambda_{eq,s}$ for the gas inside the glass block cavity, as also indicated in the standard EN 673:2011:

$$\lambda_{eq,s} = \frac{d_s}{R_s} \quad \left[\frac{W}{m\ K}\right] \qquad [7]$$

where: d_s is the thickness of the cavity; R_s is the thermal resistance of the cavity.

In particular, R_s is the inverse of the thermal conductance h_s that is defined in EN 673:2011 as the sum of the radiation conductance h_r and gas conductance h_g related to the gas space inside the glass block, taking into account both effects of radiation and convection[12].

$$R_s = \frac{1}{h_s} = \frac{1}{h_r} + \frac{1}{h_g} \quad \left[\frac{m^2K}{W}\right] \qquad [8]$$

The radiation conductance h_r depends upon the emissivity values of the surfaces delimiting the gas space and upon the mean absolute temperature of the gas space.

The gas conductance h_g, instead, depends upon the temperature difference between glass surfaces bounding the gas space, the mean temperature of the gas space[13] as well as upon is the density (ρ), the dynamic viscosity (μ), and the specific heat capacity (c) of the gas inside the cavity.

Having calculated the equivalent thermal conductivity, it is finally inserted in the software as a thermal property of the gas inside the cavity, as defined in the Comsol models[14].

Once the model in Comsol is set and the simulation are run, it is possible to obtain the thermal distribution inside the glass block and the total conductive heat flux Q_{tot} across glass block internal and external faces (expressed in W).

In particular, the graph, provided by Comsol software, illustrating the temperature distribution inside the glass block is not exactly corresponding to the actual situation, in particular as for the gas space. Indeed, the simulations only take into account the conductive heat transfer, while an equivalent thermal conductivity was introduced for the gas filling the cavity of the glass block, in order to take into account the heat transfer due to convective and radiative effects. However, the graph of the thermal distribution could be useful to compare the behavior of the different subcomponents in the various configurations.

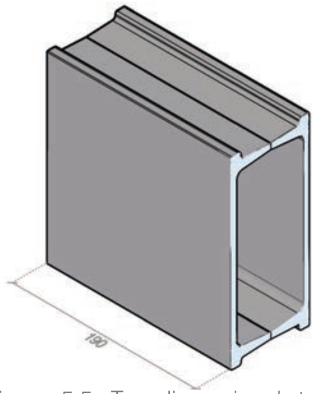


Figure. 5.5 - Two-dimensional study, with the cross section “distribution”

In 2D environment, the total conductive heat flux, provided by Comsol, is expressed in W/m and must be multiplied by the dimension of glass block section (0.19 m) to obtain the value in W. In this way, it is possible to “distribute” the results obtained for the single cross section throughout the surface of the glass block, as shown in the Figure 5.5.

The total thermal conductance of the glazing h_t, being A (m^2) the area of the glass block and ΔT (K) the temperature difference between the internal and external glazed faces, is:

$$h_t = \frac{Q_{tot}}{A \cdot \Delta T} \quad \left[\frac{W}{m^2 K}\right] \qquad [9]$$

The U value of each of the glass block configuration is thus obtained from the reciprocal of the following formula:

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i} \quad \left[\frac{m^2 K}{W}\right] \qquad [10]$$

where:

- h_e is the external heat transfer coefficient that takes into account the convective heat exchange between the external glazed surface and the surrounding environment. In the calculations its value has been considered equal to 23 W/m²K;
- h_i is the internal heat transfer coefficient, taking into account the convective heat exchange between the internal glazed surface and the surrounding environment. In the calculations, its value has been considered equal to 8 W/m²K.

Another parameter that turns out useful for the comparison of the different glass block configurations among each other as well as with other materials or products, is the equivalent thermal conductivity λ_{eq} (W/mK) that allows considering the different configurations of the glass block as if they were a single material. This parameter is calculated as the product of the total thermal conductance of the glazing h_t (W/m²K) and its thickness (m).

Once the procedure is defined and models are drawn, simulations can be launched. The results are widely discussed in the following pages.

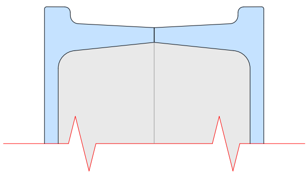
5.5.2. One-cavity Configurations

Besides the verification of "standard" glass block U value, also the influence of a polycarbonate (PC) break between the glass shells has been analyzed.

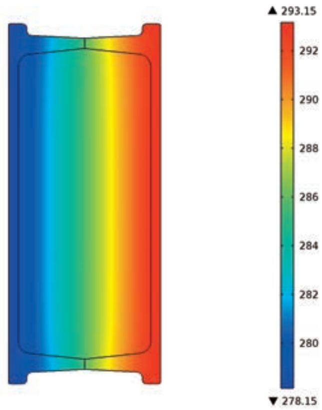
5.5.2.1. "Standard" glass block

The first configuration tested is a "standard" glass block with vacuum or air inside the cavity. The calculated U values confirmed, as for the air-filled configuration, the results obtained in previous works (Cappello et al., 2011) and in experimental tests executed on glass block samples[15]. The presence of vacuum, instead of air, inside the cavity causes an 0.4-reduction in glass block U value, in both 3D and 2D simulations.

1-2



"Standard" GB with 1 cavity		
Thickness (mm)	80	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	2.6	2.9
U Value,3D (W/m²K)	2.6	3.0

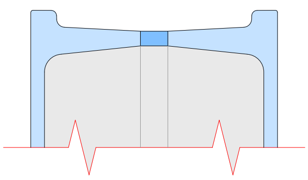


Temperature distribution, air-filled configuration

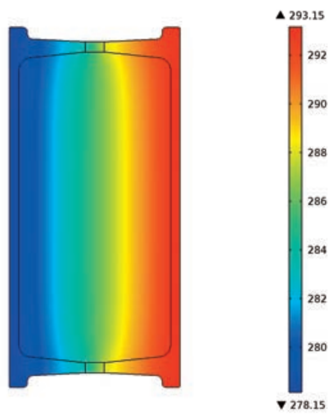
5.5.2.2. Glass block with 10-mm polycarbonate thermal break

The utilization of polycarbonate for achieving a thermal break between the two glass shells allows reducing of some points the U value of the glass block, but not to a significant extent. From the distribution of the temperatures inside the glass block with that of the "standard" glass block, it is possible to see clearly the effect of the PC break between the glass shells. A disadvantage might be the thickening of the cavity and, thus, of the whole product.

3-4



GB with 1 cavity and PC thermal break		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	2.3	2.8
U Value,3D (W/m²K)	2.3	2.8



Temperature distribution, air-filled configuration

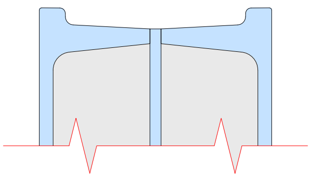
5.5.3. Two-cavity Configurations

The insertion of a sheet of transparent or translucent material (glass, PC, PC+aerogel) between the two glass shells composing the glass block is an effective way for reducing the thermal transmittance of the product. As a result, indeed, the portion of heat transfer that is related to convection decreases as well as that related to the conduction. This latter aspect, for obvious reasons, becomes of high relevance when the sheet is made of a material that is less conductive than glass (PC, PC+aerogel), since it can also create a thermal break between the glass shells.

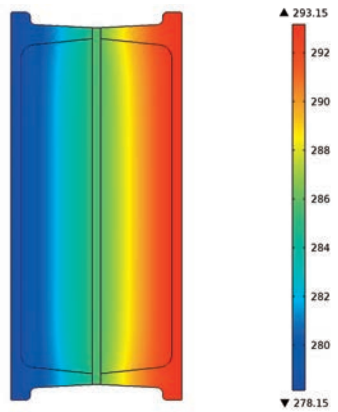
5.5.3.1. Glass block with 4-mm glass sheet

The insertion of a 4-mm glass sheet produce a significant decrease in the U value of the glass block, ranging from 0.5-0.8 W/m²K. In the air-filled configuration, this reduction is due to the reduction in the convective effect, provided by the insertion of the glass sheet,

5-6



GB with 2 cavities and 4-mm glass sheet		
Thickness (mm)	84	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.8	2.1
U Value,3D (W/m²K)	2.1	2.3

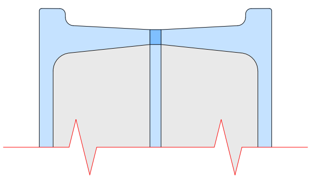


Temperature distribution, air-filled configuration

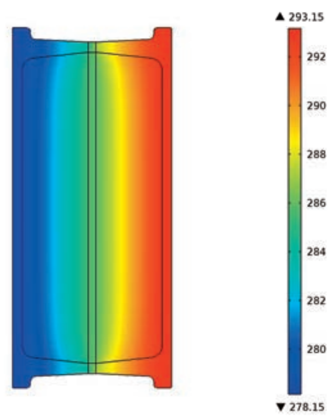
5.5.3.2. Glass block with 4-mm glass sheet and polycarbonate thermal break

The PC break does not have a relevant effect on the U value compared to the just introduced configurations (5-6); indeed, the maximum reduction observed is of 0.1 W/m²K.

7-8



GB with 2 cavities, 4-mm glass sheet and PC break		
Thickness (mm)	84	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.7	2.1
U Value,3D (W/m²K)	2.0	2.2

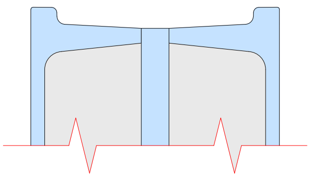


Temperature distribution, air-filled configuration

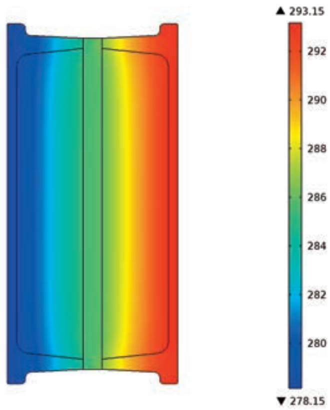
5.5.3.3. Glass block with 10-mm glass sheet

The 6-mm difference in the thickness of the glass sheet inserted inside the glass block (i.e. the only aspect that changes compared to the configuration in par. 5.5.3.1) does not have any relevant effect in the product's U value that indeed remains basically unvaried. Thus the use of a thicker glass sheet, which corresponds to higher use of materials, bigger overall product thickness and weight as well as higher costs, would not be justified in this case.

9-10



GB with 2 cavities and 10-mm glass sheet		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.8	2.1
U Value,3D (W/m²K)	2.1	2.2



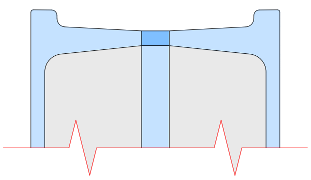
Temperature distribution, air-filled configuration

5.5.3.4. Glass block with 10-mm glass sheet and polycarbonate thermal break

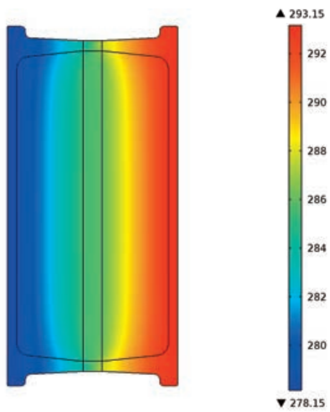
The PC thermal break leads to a certain decrease, ranging from 0.1-0.2 Wm²K, in the U value of the product with regards to the previous corresponding configurations (9-10, par. 5.5.3.3). However, the 10-mm thickness of the thermal break in PC and of the glass sheet does not produce a notable change in the U value of the product, compared to the configurations 7-8, where the same elements are 4-mm thick.

Neither in this case the higher thickness of the glass inside the cavity is "justified", because the higher material costs are not compensated by a relevant optimization of product thermal performance.

11-12



GB with 2 cavities and 10-mm glass sheet		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.7	2.0
U Value,3D (W/m²K)	1.9	2.1

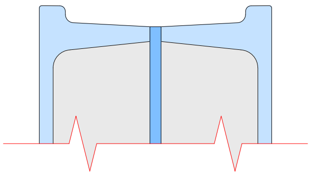


Temperature distribution, air-filled configuration

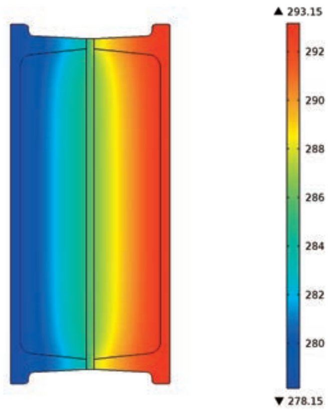
5.5.3.5. Glass block with 4-mm polycarbonate sheet and thermal break

The possibility to insert a 4-mm thick PC sheet inside the glass block, instead of a glass, has been accounted for as well. However, this does not result into a significant improvement of the U value of the product. This is probably linked to the thinness of the inserted PC sheet that does not allow exploiting sufficiently the lower conductivity of the PC (0.12 W/mK), approximately 8 times lower than that of glass (1 W/mK).

13-14



GB with 2 cavities and 4-mm PC sheet and break		
Thickness (mm)	84	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.7	1.9
U Value,3D (W/m²K)	1.9	2.1

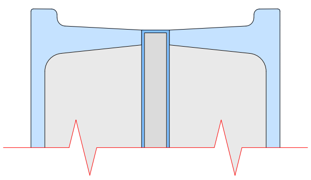


Temperature distribution, air-filled configuration

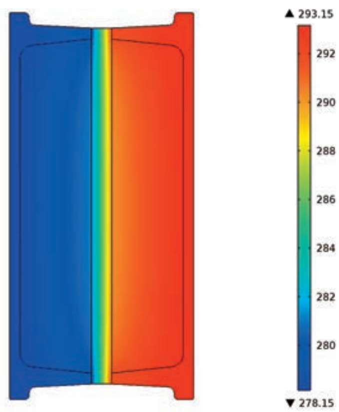
5.5.3.6. Glass block with 10-mm PC+aerogel sheet and thermal break

The combination of PC and aerogel allows obtaining sheets of translucent material with optimum insulation performance and a thermal conductivity of 0.018 W/mK (ca. 55 times lower than that of glass). De facto, the resulting U value goes down significantly below 0.9 W/m²K. Looking at the thermal distribution, it is clear how the PC+aerogel sheet functions perfectly as thermal break between the glass shells. A possible issue is linked to the necessity to ensure the mechanical as well as air and water tightness to the glass block. It should also be noted that, in this case, there is not great difference in the U value between evacuated and air-filled cavity configuration, due to the high insulation capacity of the PC+A sheet.

15-16



GB with 2 cavities and 10-mm PC+A sheet and break		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	0.8	0.9
U Value,3D (W/m²K)	0.8	0.9



Temperature distribution, air-filled configuration

5.5.4. Two-cavity Configurations with Thermal Belt

The choice of using a so-called "Thermal Belt" (ThB) has been discussed in the previous works already cited and fundamentally is made to provide to the "modified" glass block — besides the improved thermal insulation given by the thermal break and/or cavity subdivision — high mechanical resistance as well as ease of assembly.

The material chosen for the thermal belt is Nylon PA6 that meets the technical specifications required and whose thermal conductivity (0.23 W/mK) is more than four times lower than that of glass (1 W/mK). However, for the sake of completeness, the simulations regarding the hypothesis of a glass thermal belt, studied in Cappello et al. (2011), have been resumed and updated here as well. Since no thermal break between the glass shell is realized, the use of a glass thermal belt produces smaller effects on product thermal transmittance compared to the use of a thermal belt made of nylon.

For the thermal belt, two different shapes are designed: they foresee 10 and 20 mm distance between the glass shells and determine a glass block global thickness of 90 and 100 mm, respectively.

In order to evaluate preliminarily the impact of the Nylon thermal belt on the U value of the product compared to the "standard" glass block, specific simulations were executed on two 80-mm thick glass block configurations with the Thermal Belt, in the two aforementioned shapes. Results in Table 5.3 show that the U value of the "standard" glass block configuration goes down 1 and 2 decimal points, in 2D and 3D environment respectively, when assembled with the thermal belt. Therefore, the use of Nylon determines only a slight increase on product thermal resistance.

Nylon is a plastic material widely used, for example, in window frames with thermal break due to its good thermal and mechanical characteristics[16]. However, better insulating materials — that can also guarantee comparable mechanical performance as nylon — are also being searched for, in order to increase further the energy-saving benefits related to the use

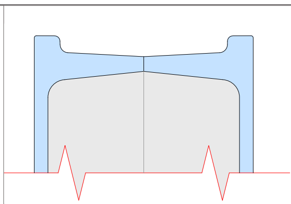
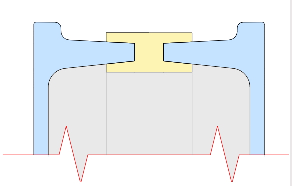
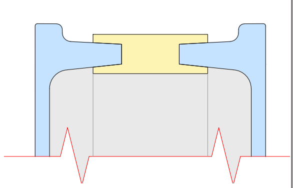
						
	"Standard" GB		1-cavity GB+Thermal Belt (10mm thermal break)		2-cavity GB+Thermal Belt (20mm thermal break)	
Thickness (mm)	80		80		80	
Cavity	Vacuum	Air	Vacuum	Air	Vacuum	Air
U Value,2D (W/m²K)	2.466 (2.5)	2.917 (2.9)	2.405 (2.4)	2.865 (2.9)	2.345 (2.3)	2.828 (2.8)
U Value,3D (W/m²K)	2.616 (2.6)	2.967 (3.0)	2.478 (2.5)	2.852 (2.9)	2.387 (2.4)	2.779 (2.8)

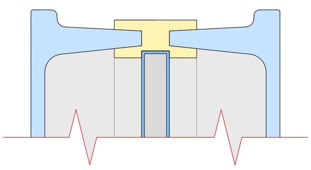
Table 5.3 - Unrounded (and rounded) U value of three 80-mm thick, one-cavity glass block configurations: "standard"; with nylon thermal belt and 10-mm thermal break; with nylon thermal belt and 20-mm thermal break

of the “thermal belt” (and, in particular, to its possibility to interrupt the thermal bridge between the outer and innermost glass shells). It must be underlined that this sub-component still serves for other technological reasons, as previously underlined (e.g. simplification in the assembly of the product; possibility to insert one or more sheets of transparent insulating material without compromising the mechanical resistance of the product; and so on...).

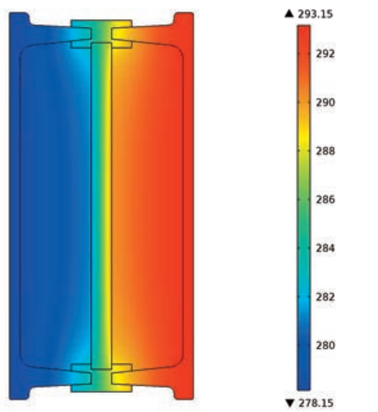
5.5.4.1. Glass block with nylon thermal belt, 10-mm break and PC+aerogel sheet

The U value of this configuration is quite efficient and notably lower than that of the “standard” glass block. However, the presence of the thermal belt, which could be necessary for several reasons already mentioned, worsens the performance of this glass block configuration with respect to those analysed in the paragraph 5.5.3.6. It is also evident from the graph of the temperature distribution inside the glass block reported below.

17-18



GB with 2 cavities, PC+A sheet and 10-mm Nylon ThB		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.3	1.4
U Value,3D (W/m²K)	1.7	1.8

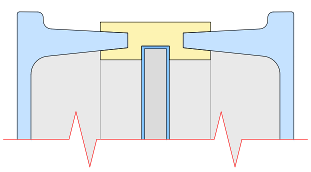


Temperature distribution, air-filled configuration

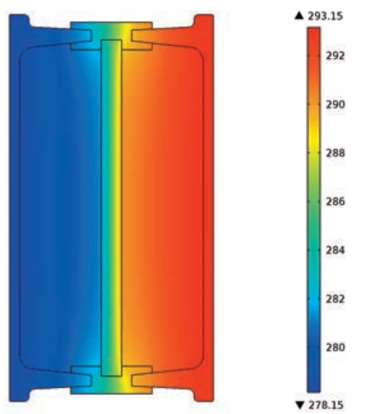
5.5.4.2. Glass block with nylon thermal belt, 20-mm break and PC+A sheet

The same considerations made in the previous paragraph are also valid in this case. The slightly thicker thermal break (increasing the global thickness to 100 mm) improves the U value of the product, but only of a small quantity, which never overcomes one decimal point.

19-20



GB with 2 cavities, PC+A sheet and 20-mm Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.2	1.3
U Value,3D (W/m²K)	1.6	1.7

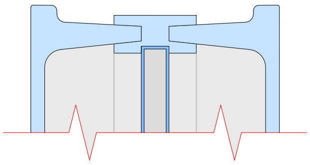


Temperature distribution, air-filled configuration

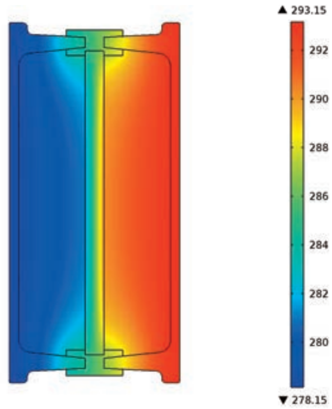
5.5.4.3. Glass block with glass thermal belt, 10-mm distance and PC+A sheet

In case of glass thermal belt, there is no thermal break between the glass shells and, as expected, this results into a higher U value than in the previous two configurations with nylon thermal belt. The heat loss that occurs through the thermal bridge that is represented by the glazed border is easily individuated in the temperature distribution graph. The rest of the glass block (i.e. the cavity) performs more effectively than this borderas for the thermal insulation.

21-22



GB with 2 cavities, PC+A sheet and 10-mm Glass ThB		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.5	1.7
U Value,3D (W/m²K)	2.0	2.1



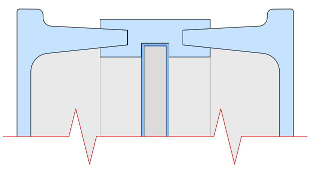
Temperature distribution, air-filled configuration

5.5.4.4. Glass block with glass thermal belt, 20-mm distance and PC+A sheet

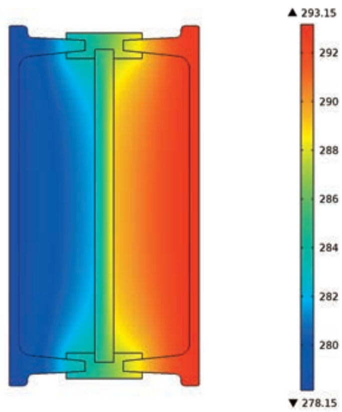
The higher thickness of the glazed thermal belt does not produce any significant improvement from the previous configuration.

It is therefore possible to conclude, that the glass thermal belt does not provide any benefit to the thermal performance of the product, whereas the one made in nylon does, even if not in a significant measure.

23-24



GB with 2 cavities, PC+A sheet and 20-mm Glass ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.5	1.6
U Value,3D (W/m²K)	1.9	2.1



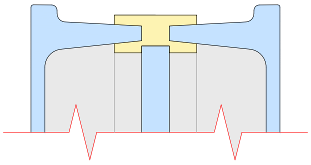
Temperature distribution, air-filled configuration

The simulations of paragraphs 5.5.4.1-4 were repeated by considering the insertion of a glass sheet, less insulating, but also more transparent and less expensive than PC+aerogel, in order to assess its effect, coupled with the thermal belt, in the overall product performance.

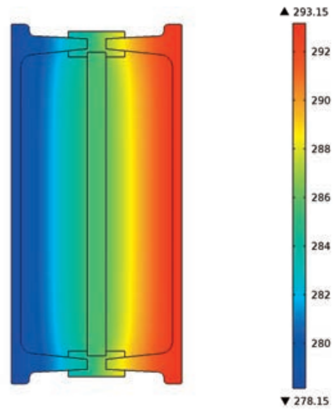
5.5.4.5. Glass block with nylon thermal belt, 10-mm break and glass sheet

In this case, the nylon thermal break helps improve the thermal transmittance of the device, as it is possible to deduct from comparing these result with those of the configurations 9-10 that are identical to these, except for the absence of the thermal belt. However, the difference in the results are not really significant and in general show a 0.1 W/m^2K decrease compared to the corresponding configurations without thermal belt.

25-26



GB with 2 cavities, Glass sheet and 10-mm Nylon ThB		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m^2K)	1.7	2.0
U Value,3D (W/m^2K)	2.0	2.1

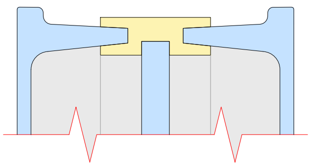


Temperature distribution, air-filled configuration

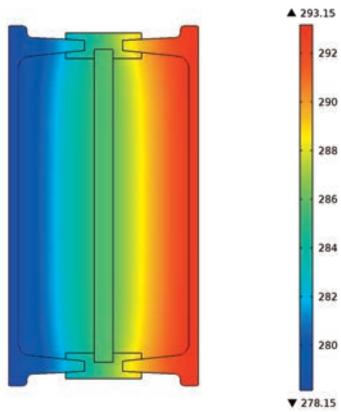
5.5.4.6. Glass block with nylon thermal belt, 20-mm break and glass sheet

The benefits deriving from the nylon thermal belt can be evidenced here as well. The 10-mm thicker thermal break (and glass block) correspond to a certain improvement in the thermal performance of the product. However, if we compare the performance of this thermal belt, characterized by a 20-mm break, with the previous one, providing a 10-mm break, the difference deriving from this specific shape of the subcomponent becomes less relevant.

27-28



GB with 2 cavities, Glass sheet and 20-mm Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m^2K)	1.7	1.9
U Value,3D (W/m^2K)	1.8	2.0



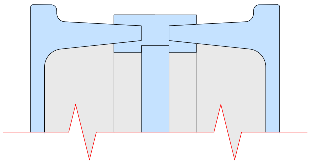
Temperature distribution, air-filled configuration

The two above-discussed configurations are analyzed also by considering to use a glass thermal belt (as in the work that the present study is updating), even if its effect is expected to be irrelevant for the improvement of glass block U value compared to that of nylon.

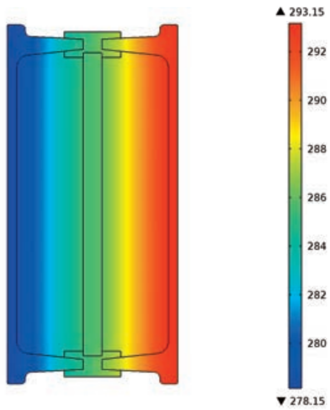
5.5.4.7. Glass block with glass thermal belt, 10-mm distance and glass sheet

Results reported below show that the absence of any thermal break between glass shells makes so that the glass ThB is not providing any benefit to the thermal performance of the product, compared to those with the same glass sheet in the cavity but no glass ThB (9-10).

29-30



GB with 2 cavities, Glass sheet and 10-mm Glass ThB		
Thickness (mm)	90	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.9	2.2
U Value,3D (W/m²K)	2.2	2.4

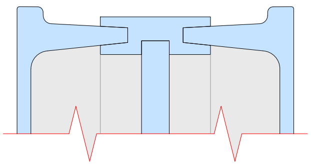


Temperature distribution, air-filled configuration

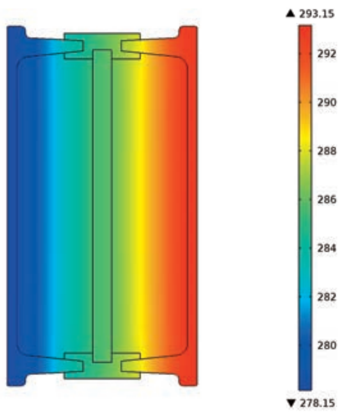
5.5.4.8. Glass block with glass thermal belt, 20-mm distance and glass sheet

Same considerations as above can be made in this case too, unless the fact that the higher thickness of the final product leads to constant 0.1 W/m²K decrease of the U value.

31-32



GB with 2 cavities, Glass sheet and 20-mm Glass ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.8	2.1
U Value,3D (W/m²K)	2.1	2.3



Temperature distribution, air-filled configuration

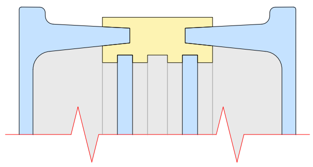
5.5.5. Three-cavity Configurations with Thermal Belt

The Thermal Belt could also be used to house two sheets of transparent, more or less insulating, materials in order to create three sub-cavities with lower thickness and further improve product performance. For these simulations the thermal belt creating a 20-mm distance between the glass shells has been "re-designed" in order to present two housing for the insertion of the sheets of different materials. In particular, the three-cavity configurations analyzed in this phase are characterized by the use of PC and glass sheet for the cavity subdivision; in two of them, aerogel is used to fill the middle sub-cavity.

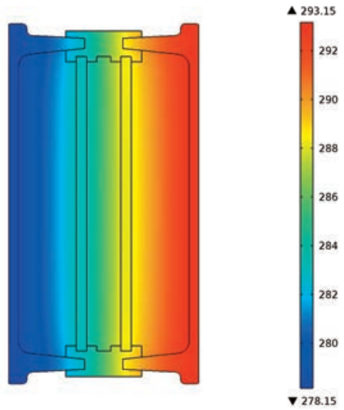
5.5.5.1. Glass block with nylon thermal belt and two 4-mm glass sheets

The insertion of two 4-mm-thick glass sheets and the subsequent quadruple glazing (with three cavities) has a very positive effect on the thermal performance of the product. If we compare the results deriving from this glass block configuration with those of the corresponding two-cavity configuration (27-28, presenting nylon thermal belt, same thermal break and 10-mm glass sheet), we can see a 2-3 decimal point decrease in the U value. This is of even greater relevance, if we consider that the amount of glass used in this case is even lower. The subdivision of the cavity into three parts is therefore a successful and simple operation for the optimization of the U value of the glass block.

33-34



GB with 3 cavities, Glass sheets and 20-mm Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.4	1.6
U Value,3D (W/m²K)	1.6	1.7

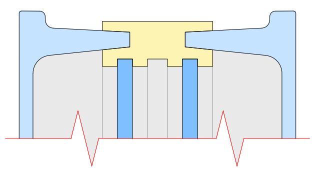


Temperature distribution, air-filled configuration

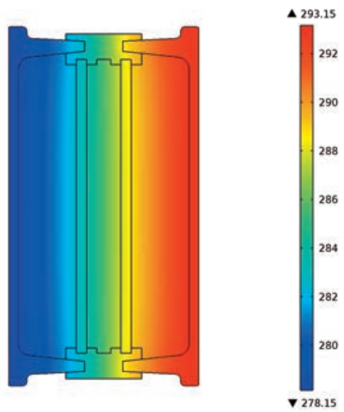
5.5.5.2. Glass block with nylon thermal belt and two 4-mm PC sheets

The use of 4-mm-thick sheets of PC for the subdivision of the cavity of the glass block, instead of 4-mm glass panes, does not produce a relevant change in the U value. Comparing the graphs that depict the temperature distribution in the these two cases, it is possible to see that PC sheets behave a little better than glazed ones[17] in terms of thermal insulation, but not sufficiently to make a substantial difference in the resulting U values[18].

35-36



GB with 3 cavities, PC sheets and 20-mm Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.4	1.5
U Value,3D (W/m²K)	1.6	1.7

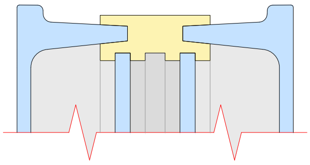


Temperature distribution, air-filled configuration

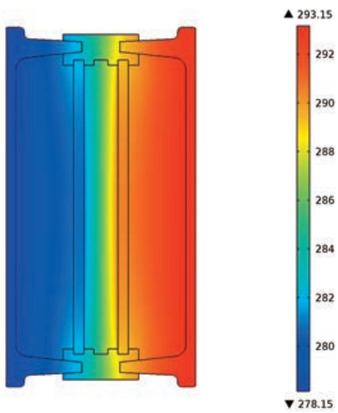
5.5.5.3. Glass block with nylon thermal belt, two 4-mm glass sheets and aerogel filling

In this configuration, aerogel is used to fill one of the three cavities (and, in particular, the middle one). This further reduces the U value of the product, compared to the three-cavity configurations that are reported in the previous two paragraphs.

37-38



GB with 3 cavities, Glass sheets, Aerogel filling, Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.2	1.2
U Value,3D (W/m²K)	1.4	1.5

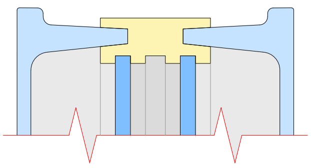


Temperature distribution, air-filled configuration

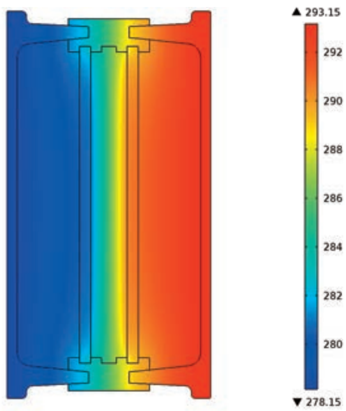
5.5.5.4. Glass block with nylon thermal belt, two 4-mm PC sheets and aerogel filling

Differently than what has been said in paragraph 5.5.5.2, here the sheet of PC generates a further improvement in the overall performance of the glass block. This is probably due to the fact that the radiative portion of the heat transfer (where polycarbonate shows a slightly worse performance than glass) is less relevant in these configurations, due to the presence of one cavity that is filled with aerogel, and therefore the benefits concerning the better heat conduction of PC compared to glass are effectively exploited here and result into an improvement, even if minor, in the U value of the product. This configuration allows reaching the best U values among all the glass blocks that present the thermal belt, but the operation of aerogel filling might imply a too expensive manufacturing as well as an increased material cost.

39-40



GB with 3 cavities, PC sheets, Aerogel filling, Nylon ThB		
Thickness (mm)	100	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.1	1.1
U Value,3D (W/m²K)	1.4	1.4



Temperature distribution, air-filled configuration

5.5.6. Two-cavity Configurations with Thermal Belt and Standard Thickness

After having reprised and updated the results provided in previous works, new configurations are also proposed and studied in this work aimed to assess the thermal transmittance of the glass block configurations that present the thermal belt and foresee the reduction of the glass shell side wings in order to achieve a "standard" 80-mm thickness of the glass block[19]. The purpose of these simulations is also to verify whether or not the increase in the global thickness of the product resulting from the insertion, between the glass shells, of the Thermal Belt is of relevance for the optimization of its thermal transmittance. The increase of standard glass block thickness, due to the insertion of the thermal belt, may indeed result in higher manufacturing costs and represent a sensitive change in the consolidated configuration of the product. Moreover, to maintain the thickness unvaried is also useful for standardization purposes, since 80-mm thick glass block with thermal belt could be installed by using the same supporting elements used for "standard" glass block.

For the sake of completeness, both the shapes of the thermal belt, considering 10-mm and 20-mm break between the glass shells, are analysed and discussed here. This means that 5 mm and 10 mm reduction in the thickness of each glass shell is arranged[20] for these two different shapes of thermal belt (the one realizing 10 mm distance and the one realizing 20 mm distance between the glass shells), as illustrated in Figure 5.6.

The configurations with thermal belt, standard thickness and 10-mm polycarbonate+ aerogel or glass sheet have been analysed and compared with those of the corresponding configurations with "increased" thickness (90 or 100mm). The results show that the slight reduction (10 or 20 mm) in the thickness of the product does not have any relevantly negative effect on its performance in terms of thermal insulation. This might be due to the fact that the reduction of glass block thickness also corresponds to a decrease in the dimension of the air cavities and, subsequently, into a reduction of the heat transfer related to convection. This aspect compensates for the lower conductive resistance that derives from the smaller thickness of the product.

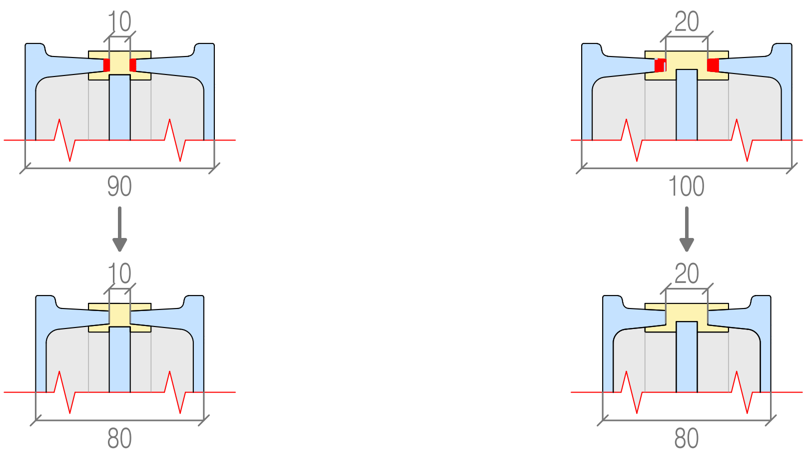


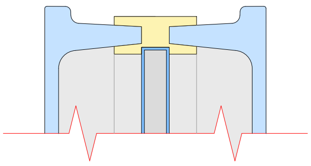
Figure. 5.6 - Illustration of the new configurations with thermal belt, characterized by 10-mm (left) and 20-mm (right) break between the glass shells, and standard thickness, obtained by reducing glass shells thickness

Therefore, for the sake of standardization as well as material (and cost) saving, the new configurations with standard thickness and thermal belt, could be considered, on an overall balance, as an interesting option to optimize glass block thermal transmittance, while maintaining the overall thickness of the product unchanged.

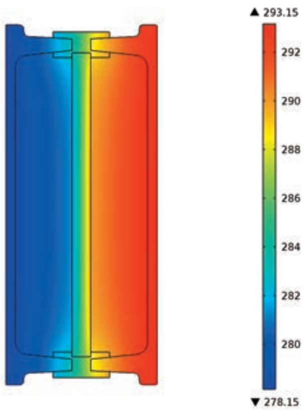
5.5.6.1. Glass block with thermal belt, standard thickness, 10-mm break and PC+A sheet

As anticipated, by comparing the results of this glass block configuration with those of the corresponding one with "increased" thickness due to the use of the thermal belt (17-18, par. 5.5.4.1), it is not possible to highlight any notable difference in the resulting U value: thus, with less material and lower costs, the same thermal performance is achieved here.

41-42



80-mm thick GB with 2 cavities, PC+A sheet, 10-mm ThB		
Thickness (mm)	80	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.3	1.4
U Value,3D (W/m²K)	1.7	1.8

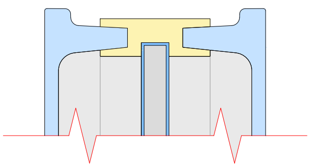


Temperature distribution, air-filled configuration

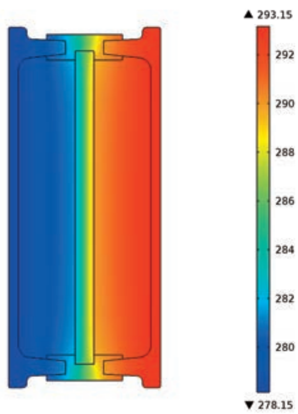
5.5.6.2. Glass block with thermal belt, standard thickness, 20-mm break and PC+A sheet

Also in this case, the reduction of the thickness of the glass shells does not cause relevant changes in the U value of the product compared to corresponding 100-mm thick configuration (19-20, par. 5.5.4.2).

43-44



80-mm thick GB with 2 cavities, PC+A sheet, 20-mm ThB		
Thickness (mm)	80	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.3	1.3
U Value,3D (W/m²K)	1.6	1.6

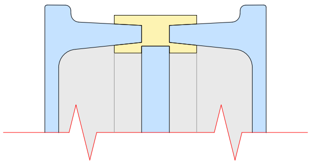


Temperature distribution, air-filled configuration

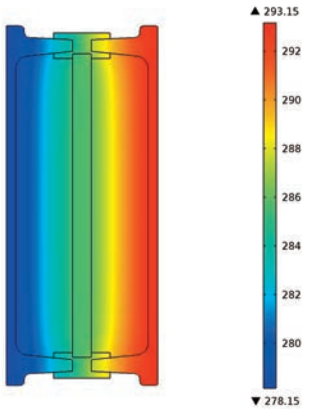
5.5.6.3. Glass block with thermal belt, standard thickness, 10-mm break and glass sheet

In this case, it is possible to highlight a basically constant (equal to 0.1 W/m²K) reduction in the U value of the product with respect to the corresponding configurations with standard, unmodified glass shells and with overall 90-mm thickness (see configurations 21-22, paragraph 5.5.4.3).

45-46



80-mm thick GB with 2 cavities, Glass sheet, 10-mm ThB		
Thickness (mm)	80	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.8	2.1
U Value,3D (W/m²K)	2.0	2.2

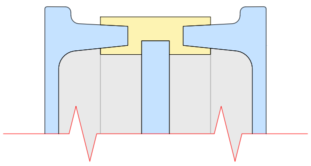


Temperature distribution, air-filled configuration

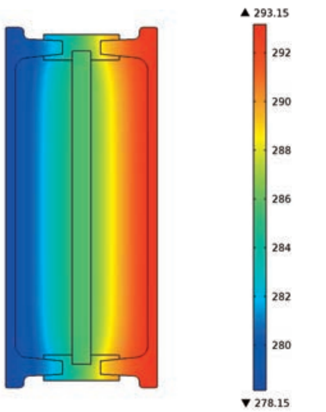
5.5.6.4. Glass block with thermal belt, standard thickness, 20-mm break and glass sheet

Also in this case, the smaller thickness of the glass block deriving from the reduction of glass shell thickness provokes a slight reduction (constant and equal to 0.1 W/m²K) in the U value of the product compared to the corresponding configurations (22-23, par. 5.5.4.4).

47-48



80-mm thick GB with 2 cavities, Glass sheet, 20-mm ThB		
Thickness (mm)	80	
Cavity	Vacuum	Air
U Value,2D (W/m²K)	1.8	2.0
U Value,3D (W/m²K)	1.9	2.1



Temperature distribution, air-filled configuration

5.5.7. Other Configurations with Thermal Belt and Low-emission Glass

Among the new thermally-optimized configurations proposed in this work, some consist in the insertion of a low-emissive glass inside the cavity by means of the appropriate housing in the Thermal Belt. This allows for further reductions in product transmittance, due to the drop of the radiative heat transfer portion, which is very important, especially in glazing systems. Some of the best U value ranges among all the studied configurations have been achieved with this operation that, differently than in the other "groups" of glass block configurations, is specifically addressed to cut down the radiative part of the heat transfer, besides the convective and conductive ones.

Both the above-presented shapes of the thermal belt (providing 10-mm and 20-mm break) have been analyzed, by considering also the reduction of the thickness of the glass shells in order to achieve the standard 80-mm thickness of the product. All configurations also take into account the possibility to use argon to fill the cavity of the glass block; this operation has also been proposed by the glass block company SEVES in order to improve the thermal transmittance of its products[21].

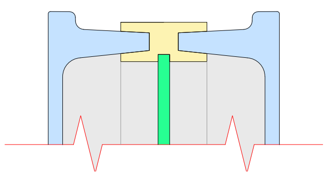
Moreover, among the new configurations involving the use of the thermal belt and of a low emissive glass sheet, it has also been analysed the possibility to have a quadruple glazing with three-cavities (as discussed in paragraph 5.5.5) and with one of the two inner glass sheets being low-emissive. In particular, the glass sheet has been positioned with the low-emissive coating (that has a very low emissivity, equal to 0.0387) on the "colder" side, closer to the outdoor environment[22].

As previously underlined, simulations are based only on the conduction, whereas the radiation and convection across the gas spaces are accounted for by means of an equivalent thermal conductivity that is evaluated analytically, according to the methodology indicated in the standard EN 673:2011, and later assigned to the gas of the cavities. The gas in contact with the low-emission coating results notably less conductive than the other/s. This can be easily visualized in the asymmetry of the graphs depicting the temperature distribution in the various configurations.

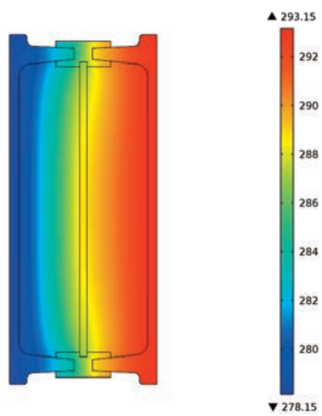
5.5.7.1. Glass block with thermal belt, standard thickness, 10-mm break and low-e sheet

The low-e glass sheet inside the cavity causes a notable improvement in glass block performance, compared, for example, with the corresponding glass block configuration without low-e coating (45-46, paragraph 5.5.6.3). U values go down of 0.3-0.7 W/m^2K.

49-50-51



80-mm thick GB with 2 cavities, Low-e sheet, 10-mm ThB			
Thickness (mm)	80		
Cavity	Vacuum	Air	Argon
U Value,2D (W/m^2K)	1.1	1.6	1.5
U Value,3D (W/m^2K)	1.5	1.8	1.7



Temperature distribution, air-filled configuration

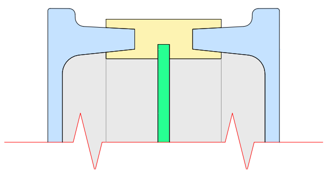
5.5.7.2. Glass block with thermal belt, standard thickness 20-mm break and low-e sheet

As in the previous case, it is possible to see directly the effect deriving from the insertion of low-e glass instead of glass by looking at the corresponding configuration without low-e coating (47-48, paragraph 5.5.6.4).

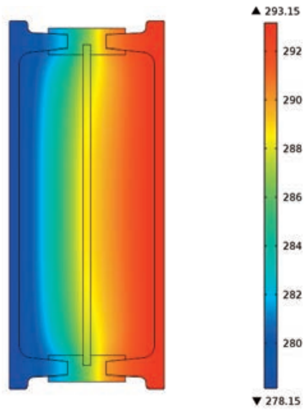
Instead, compared to the previous configurations (49-50-51), the 10-mm bigger distance between the glass shells leads to 0.1-0.2 W/m²K decrease in the U value.

Argon is a more insulating gas than air and its use results into a 0.1 W/m²K[23] reduction in the U value of the glass block compared to air-filled configuration. Such effect however does not seem to be very significant, even if it can make the difference when specific limits in the U values of glazing are imposed.

52-53-54



80-mm thick GB with 2 cavities, Low-e sheet, 20-mm ThB			
Thickness (mm)	80		
Cavity	Vacuum	Air	Argon
U Value,2D (W/m²K)	1.0	1.5	1.4
U Value,3D (W/m²K)	1.3	1.6	1.6

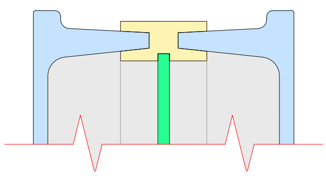


Temperature distribution, air-filled configuration

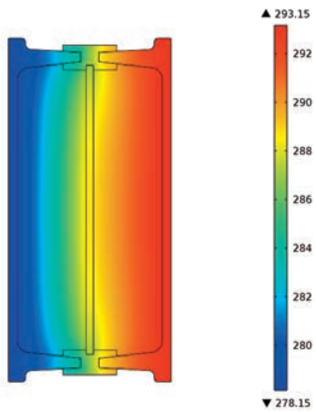
5.5.7.3. Glass block with thermal belt, 10-mm break and low-e sheet

The only difference from configurations 49-51 (par. 5.5.7.1) is the 90-mm thickness, due to the absence of any measure to reduce glass shell thickness for the maintenance of the standard 80-mm thickness of the product. Compared to those, the U values here go down 1 decimal point in 2D analyses and do not change at all in 3D analyses. This means that the increased thickness is not justified by any notable improvement in thermal performance.

55-56-57



90-mm thick GB with 2 cavities, Low-e sheet, 10-mm ThB			
Thickness (mm)	90		
Cavity	Vacuum	Air	Argon
U Value,2D (W/m²K)	1.0	1.5	1.4
U Value,3D (W/m²K)	1.5	1.8	1.7



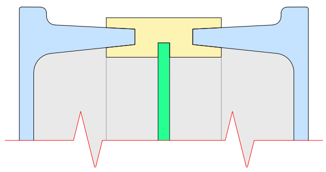
Temperature distribution, air-filled configuration

6.5.7.4. Glass block with thermal belt, 20-mm break and low-e sheet

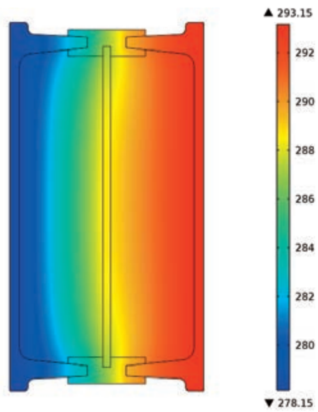
The only difference from configurations 52-54 (paragraph 5.5.7.2) is the 20-mm bigger thickness that generates, in the U value of the product, a decrease that never overcomes 0.1 W/m²K.

Also in this case, the bigger amount of materials deriving from the 100-mm thickness of the glass block (and the related increase in its economic cost) is not compensated by a notable improvement of the thermal transmittance. Configurations 52-54 could therefore be preferred on an overall balance.

58-59-60



100-mm thick GB with 2 cavities, Low-e sheet, 20-mm ThB			
Thickness (mm)	100		
Cavity	Vacuum	Air	Argon
U Value,2D (W/m²K)	0.9	1.4	1.3
U Value,3D (W/m²K)	1.3	1.7	1.6



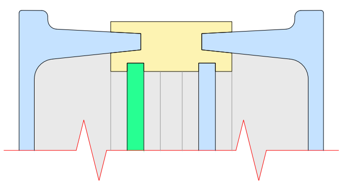
Temperature distribution, air-filled configuration

6.5.7.5. Glass block with thermal belt, two 4-mm glass sheets (one of which low-e)

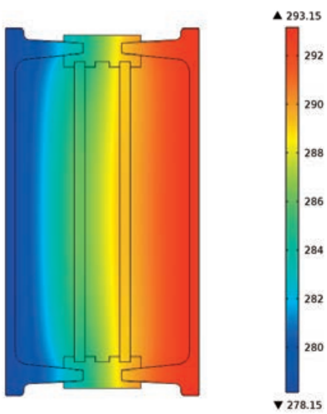
The U value of this configuration is the lowest within this “group” of new configurations involving low-emission glass sheets, both in 2D and 3D simulative environments. However, also in this case, differences are not very significant.

Instead, if we compare these results, with those obtained in configurations 33-34 (par. 6.5.5.1) — that are identical to these unless of the absence of the low-emissive glass — the improvement in the U value is more important. The U value decrease that is linked to the use of low-emission glass sheet, de facto, reaches up to 0.4 W/m²K.

61-62-63



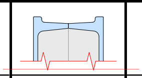
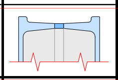
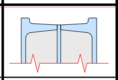
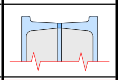
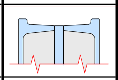
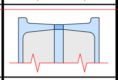
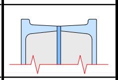
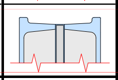
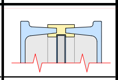
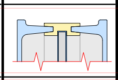
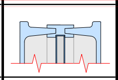
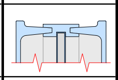
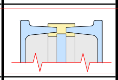
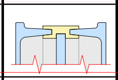
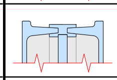
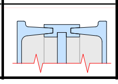
100-mm thick GB with 3 cavities, Low-e and glass sheet			
Thickness (mm)	100		
Cavity	Vacuum	Air	Argon
U Value,2D (W/m²K)	1.0	1.3	1.2
U Value,3D (W/m²K)	1.3	1.5	1.5



Temperature distribution, air-filled configuration

5.5.8. Summary and Discussion of the Results

The results are summarized in Table 5.4, where they are compared with those obtained in previous works and, when possible, coupled with related g-value and visible transmittance[24].

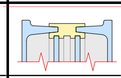
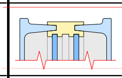
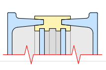
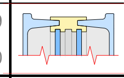
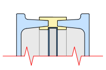
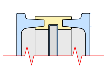
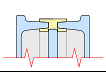
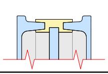
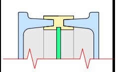
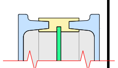
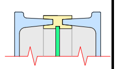
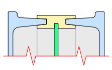
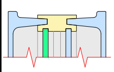
				Thickness (cm)	Thermal Break	Thermal Belt	Sheet Material	2015		λeq		2010		2010	
								2D	3D	2D	3D	2D	3D	g	Tv
1 Cavity	V	1		8	-	-	-	2,5	2,6	0,338	0,374	1,0	1,6	71%	81%
	A	2		8	-	-	-	2,9	3,0	0,459	0,475	2,9	3,0	71%	81%
	V	3		9	PC	-	-	2,3	2,3	0,342	0,346	0,4	0,9	71%	81%
	A	4		9	PC	-	-	2,8	2,8	0,486	0,468	2,6	2,8	71%	81%
2 Cavities	V	5		8,4	Glass	-	Glass	1,8	2,1	0,220	0,278	0,9	1,5	62%	76%
	A	6		8,4	Glass	-	Glass	2,1	2,3	0,267	0,316	2,0	2,4	62%	76%
	V	7		8,4	PC	-	Glass	1,7	2,0	0,207	0,255	0,6	1,4	62%	76%
	A	8		8,4	PC	-	Glass	2,1	2,2	0,269	0,300	2,0	2,3	62%	76%
	V	9		9	Glass	-	Glass	1,8	2,1	0,228	0,286	0,9	1,5	58%	71%
	A	10		9	Glass	-	Glass	2,1	2,2	0,291	0,326	2,0	2,3	58%	71%
	V	11		9	PC	-	Glass	1,7	1,9	0,214	0,248	0,6	1,2	58%	71%
	A	12		9	PC	-	Glass	2,0	2,1	0,278	0,302	1,9	2,2	58%	71%
	V	13		8,4	PC	-	PC	1,7	1,9	0,194	0,235	0,7	1,2	58%	75%
	A	14		8,4	PC	-	PC	1,9	2,1	0,235	0,269	1,9	2,1	58%	75%
	V	15		9	PC+A	-	PC+A	0,8	0,8	0,085	0,087	0,1	0,3	52%	49%
	A	16		9	PC+A	-	PC+A	0,9	0,9	0,097	0,095	0,9	0,9	52%	49%
2 Cavities + Thermal Belt	V	17		9	Nylon	Nylon	PC+A	1,3	1,7	0,151	0,220	0,8	1,3	52%	49%
	A	18		9	Nylon	Nylon	PC+A	1,4	1,8	0,164	0,234	1,4	1,8	52%	49%
	V	19		10	Nylon	Nylon	PC+A	1,2	1,6	0,145	0,214	0,7	1,1	52%	49%
	A	20		10	Nylon	Nylon	PC+A	1,3	1,7	0,161	0,232	1,3	1,7	52%	49%
	V	21		9	-	Glass	PC+A	1,5	2,0	0,186	0,269	0,9	1,4	52%	49%
	A	22		9	-	Glass	PC+A	1,7	2,1	0,215	0,295	1,6	2,1	52%	49%
	V	23		10	-	Glass	PC+A	1,5	1,9	0,193	0,289	0,9	1,4	52%	49%
	A	24		10	-	Glass	PC+A	1,5	2,1	0,205	0,318	1,4	2,0	52%	49%
	V	25		10	Nylon	Nylon	Glass	1,7	2,0	0,247	0,293	0,8	1,3	58%	71%
	A	26		10	Nylon	Nylon	Glass	2,0	2,1	0,293	0,336	2,0	2,2	58%	71%
	V	27		10	Nylon	Nylon	Glass	1,7	1,8	0,230	0,260	0,7	1,2	58%	71%
	A	28		10	Nylon	Nylon	Glass	1,9	2,0	0,283	0,304	1,9	2,2	58%	71%
	V	29		9	-	Glass	Glass	1,9	2,2	0,249	0,315	0,9	1,5	58%	71%
	A	30		9	-	Glass	Glass	2,2	2,4	0,311	0,362	2,1	2,4	58%	71%
	V	31		10	-	Glass	Glass	1,8	2,1	0,263	0,326	0,9	1,4	58%	71%
	A	32		10	-	Glass	Glass	2,1	2,3	0,336	0,387	2,0	2,4	58%	71%

Materials Legend

- Glass
- Polycarbonate
- Nylon
- Gas Space (Air/Vacuum/Argon)
- Low-e glass block
- Aerogel

Very Efficient	U < 1.3
Efficient	1.3 < U < 1.7
Poorly efficient	1.7 < U < 2.0
Not efficient	2.0 < U

Table 5.4 *(continues in the next page)* - Summary of results: 2015 U value (W/m²K), λeq (in W/mk) and, when possible, 2010 U value (W/m²K), g-value and visible transmittance, Tv

				Thickness (cm)	Thermal Break	Thermal Belt	Sheet Material	2015		λeq		2010		2010	
								2D	3D	2D	3D	2D	3D	g	Tv
3 Cavities + Thermal Belt	V	33		10	Nylon	Nylon	Glass	1,4	1,6	0,188	0,223	0,8	1,3	55%	69%
	A	34		10	Nylon	Nylon	Glass	1,6	1,7	0,212	0,242	1,6	1,9	55%	69%
	V	35		10	Nylon	Nylon	PC	1,4	1,6	0,179	0,218	0,8	1,3	50%	62%
	A	36		10	Nylon	Nylon	PC	1,5	1,7	0,198	0,234	1,6	1,9	50%	62%
	V	37		10	Nylon	Nylon	Glass	1,2	1,4	0,145	0,191	0,8	1,3	41%	42%
	A	38		10	Nylon	Nylon	Glass	1,2	1,5	0,151	0,197	1,2	1,7	41%	42%
	V	39		10	Nylon	Nylon	PC	1,1	1,4	0,138	0,188	0,8	1,3	41%	40%
	A	40		10	Nylon	Nylon	PC	1,1	1,4	0,143	0,191	1,1	1,6	41%	40%
NEW CONFIGURATIONS: 2 (or 3) Cavities + Thermal Belt	V	41		8	Nylon	Nylon	PC+A	1,3	1,7	0,137	0,193	-	-	-	-
	A	42		8	Nylon	Nylon	PC+A	1,4	1,8	0,146	0,203	-	-	-	-
	V	43		8	Nylon	Nylon	PC+A	1,2	1,6	0,118	0,171	-	-	-	-
	A	44		8	Nylon	Nylon	PC+A	1,3	1,6	0,127	0,180	-	-	-	-
	V	45		8	Nylon	Nylon	Glass	1,8	2,0	0,210	0,246	-	-	-	-
	A	46		8	Nylon	Nylon	Glass	2,1	2,2	0,254	0,280	-	-	-	-
	V	47		8	Nylon	Nylon	Glass	1,8	1,9	0,201	0,226	-	-	-	-
	A	48		8	Nylon	Nylon	Glass	2,0	2,1	0,242	0,260	-	-	-	-
	V	49		8	Nylon	Nylon	Low-e	1,1	1,5	0,110	0,167	-	-	-	-
	A	50		8	Nylon	Nylon	Low-e	1,6	1,9	0,173	0,217	-	-	-	-
	Ar	51		8	Nylon	Nylon	Low-e	1,5	1,7	0,158	0,196	-	-	-	-
	V	52		8	Nylon	Nylon	Low-e	1,0	1,3	0,098	0,138	-	-	-	-
	A	53		8	Nylon	Nylon	Low-e	1,5	1,6	0,162	0,182	-	-	-	-
	Ar	54		8	Nylon	Nylon	Low-e	1,4	1,6	0,147	0,171	-	-	-	-
	V	55		10	Nylon	Nylon	Low-e	1,0	1,5	0,123	0,197	-	-	-	-
	A	56		10	Nylon	Nylon	Low-e	1,5	1,8	0,204	0,259	-	-	-	-
	Ar	57		10	Nylon	Nylon	Low-e	1,4	1,7	0,183	0,239	-	-	-	-
	V	58		10	Nylon	Nylon	Low-e	0,9	1,3	0,104	0,165	-	-	-	-
	A	59		10	Nylon	Nylon	Low-e	1,4	1,7	0,187	0,229	-	-	-	-
	Ar	60		10	Nylon	Nylon	Low-e	1,3	1,6	0,167	0,213	-	-	-	-
	V	61		10	Nylon	Nylon	Low-e + Glass	1,0	1,3	0,120	0,171	-	-	-	-
	A	62		10	Nylon	Nylon	Low-e + Glass	1,3	1,5	0,166	0,204	-	-	-	-
	Ar	63		10	Nylon	Nylon	Low-e + Glass	1,2	1,5	0,149	0,192	-	-	-	-

Materials Legend

- Glass
- Polycarbonate
- Nylon
- Gas Space (Air/Vacuum/Argon)
- Low-e glass block
- Aerogel

Very Efficient	U < 1.3
Efficient	1.3 < U < 1.7
Poorly efficient	1.7 < U < 2.0
Not efficient	2.0 < U

Table 5.4 *(continues from the previous page)* - Summary of results: 2015 U value (W/m²K), λeq (in W/mk) and, when possible, 2010 U value (W/m²K), g-value and visible transmittance, Tv

Over 60 different configurations were analyzed through the use of Comsol Multiphysics. The differences between the 2014 and 2010 results hardly ever overcome 1 decimal point in the case of air-filled cavity/ies, enabling to make comparisons among the results as well as to argue that the methodology has been correctly replicated. The difference might be due to slight differences in the models[25]. In some cases (in particular, in the configurations presenting evacuated cavity/ies), due to the correction of some inaccuracies related to the calculation of the equivalent thermal conductivity, recalculated U values are significantly different from those obtained in the previous analyses. New configurations, besides the updated ones, have been studied as well (see rows from 41 to 63).

The results show a sharp difference in the U value computed in the cross section in 2D environment and in the glass block in the 3D environment[26]. Studying more in depth the results, the analyses on two-dimensional models are characterized, in general, by better U values. The difference between 2D and 3D results turns out to be more accentuated, for example, in the configurations where the cavity is characterized by very high insulation capacity (e.g. evacuated cavities, low-emissive glass or PC+A sheet insertion, etc.). Indeed, the cavity shows a bigger contribution to the glass block thermal performance in the two-dimensional setting of the problem than in the three-dimensional one. Conversely, the border has a more relevant role in the three-dimensional setting of the problem than in the two-dimensional one. In general, it is characterized by a worse performance in terms of thermal insulation than the center of the glass block, except e.g. for the configurations where it is thermally broken by highly insulating PC+A sheet (15-16) or where it presents nylon thermal belt and a low-insulation cavity. As a result, U values in 3D environment are in general lower than those obtained in 2D simulations.

Compared to standard glass block U value, which stands at about 2.9-3.0 W/m^2K, significantly lower values were achieved in new thermally-optimized configurations, reaching up to 0.8 W/m^2K.

The evacuation of glass block cavity on the product U value fundamentally produces a significant reduction in the conductive and convective portion of the heat transfer, but it does not have an effect on the part that is connected to radiation. As highlighted in several studies on the subject (e.g. Garrison & Collins, 1995), to create and maintain vacuum inside a glazing is a quite difficult operation that gets even more complicated as the thickness of the cavities increase. Glass block cavity is significantly thicker than that of flat glass. Moreover, in some of the above configurations, nylon or polycarbonate elements are glued to the glass shells forming the glass block and used as boundary layers of evacuated spaces. An in-depth study of their tightness, that is strictly connected to the diffusivity of the materials and of the gluing boundary should be undertaken. This would help to establish whether these configurations (as they are or integrated with appropriate elements or materials for ensuring water tightness) are able to maintain a vacuum or not and, thus, whether or not they are practically feasible.

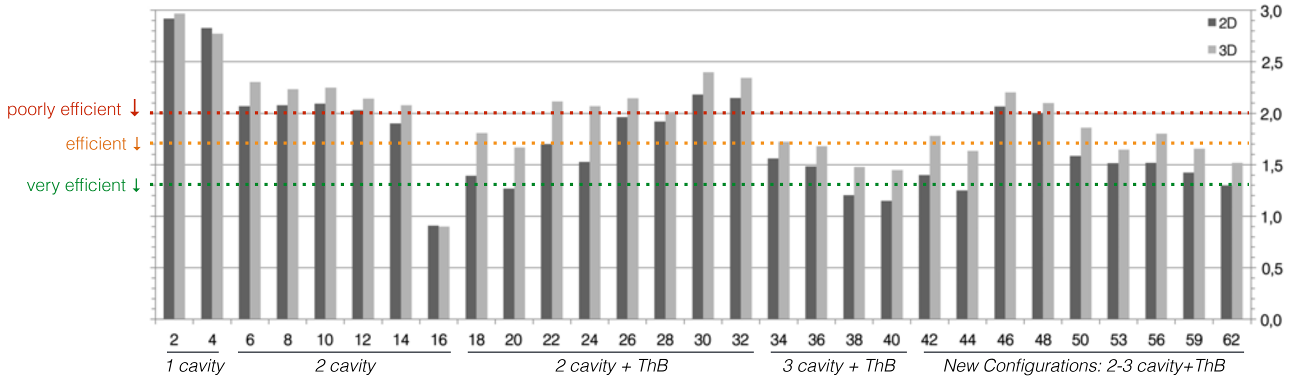


Figure 5.6 - Graph summarizing the results of the air-filled configurations

However, through the use of appropriate subcomponents, quite efficient U values have been reached also in configurations characterized by air-filled cavity (as summarized in the graph provided in Figure 5.6). For example, the insertion of a sheet of transparent or translucent material (glass, PC, PC+aerogel) inside glass block cavity is a very effective way to reduce the thermal transmittance of the product. As a result, indeed, the portion of heat transfer that is related to both conduction and convection decreases. For example, the insertion a 4-mm glass sheet inside glass block cavity determines a significant 8-decimal-point decrease (from 2.9 to 2.1 W/m^{2}K in air-filled GB configuration) in the U value of the product. Variations in the thickness of the glazed sheet is not relevant in the U value of the product, since simulations (that are not reported here) on two glass block models, with respectively 4-mm and 10-mm sheet, have produced basically identical results.

The insertion of a PC+aerogel sheet is significantly more effective for the reduction of product U value than that of a clear glass. This is fundamentally due to aerogel conductivity, which is notably lower than that of glass. However, a great difference in the final aspect of the product — which becomes translucent — can be registered. Indeed, if a high definition of the vision through the glass block is required, this configuration, although more insulating, can not be taken into consideration. As the previous studies have underlined, using a PC+aerogel sheet instead of a glazed one reduces of 22 points product visible transmittance, which goes from 71% (rows 9-10) to 59% (rows 15-16)[27].

If the inserted sheet is a low-emission glass, glass block U value goes down further, thanks to the reduction of a relevant portion of the heat transfer that is related to radiation. Furthermore, a less significant drop in visible transmittance and a more nitid view through the glass block are expected. The optical relapses related to the insertion of a low-emission glass sheet will be analyzed later in this work, but here it is sufficient to underline that different types of low-emissive coatings can be applied on a glazing and can produce significantly different results in terms of optical and solar properties. With respect to simple glass sheet insertion, this could lead to an increase of product cost, which , however, in a potential application could be balanced with the energy-saving related benefits of this solution, able to lead to some of the best U values among the analyzed configurations, up to 0.9 W/m^{2}K.

Not all configurations are characterized by the same thickness, which ranges from 80 mm (i.e. the “standard” thickness) to 84, 90, and 100 mm, depending on the thickness of the sub-components added to separate the glass shells in the different configurations. As previously underlined, for standardization purposes, in some of the new configuration glass shell thickness was reduced in order to obtain 80-mm thick glass block, even when they are assembled with the Thermal Belt. The objective was also to understand the eventual relapses on product performance related to the decrease in the thickness of the cavity and, consequently, of the product. The lower thickness does not generate significant changes in the thermal performance of the product, especially in air-filled configurations. This can also be understood by comparing, for example: rows 41-42 with 17-18; rows 43-44 with 19-20; rows 45-46 with 25-26; and rows 47-48 with 27-28. Therefore, reduction of glass shell thickness results an acceptable measure that allows maintaining glass block thickness to the 80mm and does not provoke any interestingly negative effects on product performance.

The separate study of the effect of the thermal break between the glass shells due to the nylon thermal belt on the U value — assessed as described in paragraph 5.5.4 and shown in Table 5.3 — allowed evaluating the contribution of this subcomponent to the reduction of the conductive heat transfer. Such contribution corresponds to 1 to 2 decimal point reduction of the U value of the product and, therefore, it alone is not sufficient to justify the use of the Thermal Belt. However, as already anticipated, it could be very useful to ensure ease of assembly and mechanical tightness to the product and, if further optimized, it could also be of relevance to interrupt the continuity between the inner and outer shells composing the glass block. De facto, this continuity that characterizes the “border” of the product is the main issue that needs to be addressed to maximize product thermal resistance[28]. In particular, the use of a material more insulating than nylon for the thermal belt (better if the one with 20-mm break between glass shells) could help minimize the glass block thermal transmittance and reach very efficient U values.

De facto, when a PC+aerogel layer is inserted between one glass shell and the other, as in the configurations 15-16, the deriving thermal break becomes even more relevant for the conductive heat transfer across the glass block. As a result, such configurations, both air-filled and evacuated, allow reaching the best U value among all the studied ones (0.8-0.9 W/m^2K). However, other issues affecting the manufacturing, tightness, mechanical resistance of the product can occur with respect to the same configurations unless of the presence of the thermal belt (17-20, 41-44). Here the U values are still efficient and range from 1.2-1.8 W/m^2K, but it is clear that there is a drop in the performance of the product when the PC+A thermal break between the glass shells is substituted by the less insulating nylon.

It should be noted that the thermal belt is of relevance also in the perspective of the integration of a PV module inside the glass block since it can manage, by means of one or more sub-components, the relation with the plastic profiles that house the supporting structures and electrical interconnections of the panels. The relapses on the optical performance of the glass block deriving from the use of the thermal belt are discussed later in this chapter.

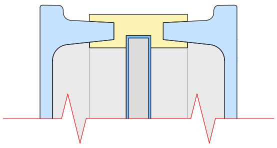
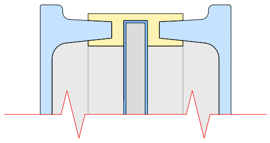
				
	"Basic" Thermal Belt		"Redesigned" Thermal Belt	
Cavity	Vacuum	Air	Vacuum	Air
U Value,2D (W/m^2K)	1.182 (1.2)	1.250 (1.3)	1.029 (1.0)	1.097 (1.1)
U Value,3D (W/m^2K)	1.569 (1.6)	1.634 (1.6)	1.163 (1.2)	1.216 (1.2)

Table 5.5 - Unrounded (and rounded) U value of the configurations 43-44 with basic and redesigned thermal belt

Besides using a material more insulating than nylon for the thermal belt, equally performing in terms of e.g. mechanical resistance[29], another solution to improve further the thermal insulation of the glass block border can entail the re-design of the thermal belt. The latter, e.g., can be re-modeled in order to allow for the presence of one or more housing that can be filled with highly insulating materials or left hollow in order to create a non-ventilated cavity, thus reducing overall glass block thermal performance as well as its weight. All that, compatibly with all other technological requirements the subcomponent needs to fulfill.

In this sense, a new version of this subcomponent has been simulated in one of the configurations already analyzed (and, in particular, in the configuration characterized by standard thickness, 20-mm break and PC+aerogel sheet, rows 43-44). The housing of the PC+A sheet has been extended in order to occupy a more relevant portion of the thermal belt section, as illustrated in Table 5.5, where results are shown as well as compared with those already discussed regarding the basic thermal belt shape; such modification of the thermal belt seems already very promising, since it allows for a significant reduction in the U value of the product (reduction around 0.4 W/m^2K in 3D simulations).

Besides the advantages related to the lower U value and smaller weight, the subtraction of material in the cross section could also allow for the realization of housing which, in the perspective of a PV integration, would allow for the positioning of elements for the interconnection of modules. In the light of all these considerations, new "designs" of this sub-component (as well as the other plastic elements) have been recently developed.

5.5.9. Simulations on "framed" glass blocks

For a preliminary evaluation of the effects, in terms of thermal transmittance, of the supporting structure of glass block panels, made of plastic moulded profiles, simulations have also been executed on a single "framed" glass block. This means that a single glass block, rounded by 2 half profiles in 2D environment, was simulated in Comsol; this is representative of the basic sub-components of the panel. Steel bars were taken into consideration as well. Same boundary conditions as in the previous analyses were applied and the same methodology explained in paragraph 5.5.1 was used. However, to begin, not all configurations were taken into account, but only "standard" glass block. In order to compare the "traditional"

Materials properties	Thermal conductivity, λ (W/mK)	Density, ρ (kg/m³)
Traditional mortar	1.000	1700
Enlightened mortar	0.28	800
Nylon PA6	0.230	1140
Nylon PA6+glass fibres	0.300	1350
PLA	0.130	1240
Steel	44.5	7850

Table 5.6 - Physical properties of the materials used for the supporting structure in the calculations

wet assembly system based on mortar (traditional or enlightened, as indicated in SEVES Glass Block, 2006) with the patented dry assembly system with profiles in nylon PA6 (with and without glass fibers), different simulations were run, by taking into account different materials, with the properties reported in Table 5.6. Analyses also considered PLA (Polylactide) that, besides the good insulation performance, has also been proven in previous works (Pollicino, 2015; La Barbera, 2015) as a well structurally performing material for the realization of the moulded profiles of the dry-assembled glass block panels, since it provides a good compromise between mechanichal strength and deformability.
As indicated in the standard ISO 15099: «…*The total properties of window and door products are calculated by combining the various component properties weighted by either their respective projected areas or visible perimeter. The total properties are based on total projected area occupied by the product, At...*». All properties must be weighted on the basis of the area effectively occupied by the glazing and by the frame, as in the equation below:

$$U_t = \frac{\Sigma A_{gv}U_{gv} + \Sigma A_f U_f + \Sigma l\psi\Psi}{A_t} \quad [11]$$

where A_{gv} and A_f are the projected vision and frame area. The length of the vision area perimeter is l_ψ and ψ is a linear thermal transmittance that accounts for the interaction between frame and glazing[30].
In the glass block, for the analysis of the dry-assembled panel performance, we can consider the schematization illustrated in Figure 5.7:

- as A_{gv} the area of the glazed surfaces including the border (set equal to 0.0318 m²);
- as A_f the projected area of the support structure (set equal to 0.0043 m²).

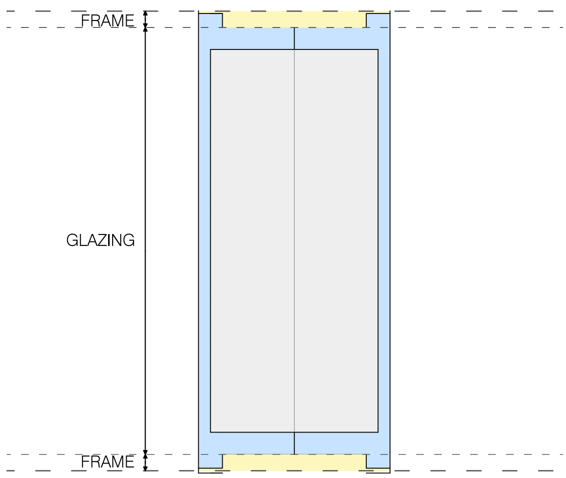


Figure 5.7 - Simplified glass block cross section illustrating what is meant for frame and glazing

Simulations with Comsol on both “unframed” and “framed” glass block (i.e. without and with supporting structure, respectively) were run and, in order to evaluate the contribution of the frame (U_f) to the simulated total U value of the product (U_t), Equation [5] was used. The results are illustrated in Table 5.7, where the U value provided by SEVES for the standard Q19 glass block, “unframed” and “framed” with traditional or enlightened mortar, in order to allow for some preliminary comparisons with the new assembly system proposed in this work.

	SEVES	Comsol 2D	
	Glass block (Ut)	Glass block (Ut)	Profiles (U_f)
standard Q19, unframed	2.8	2.9	-
standard Q19, framed by traditional mortar	3.0	3.2	4.0
standard Q19, framed by enlightened mortar	2.8	3.0	2.9
standard Q19, framed by nylon PA6	-	3.0	2.7
standard Q19, framed by nylon PA6+glass fibres	-	3.0	2.8
standard Q19, framed by PLA	-	2.9	2.5

Table 5.7 - U value of “framed” and “unframed” glass blocks: results from Comsol 2D simulations and values provided by SEVES

As shown in Table 5.7, a slightly different U value than the one provided by SEVES was calculated; this difference may be due to the input data used in the program, which can differ from the actual properties of the materials in the experimental measurements, especially as for gas properties, or to the small corrections applied in the models for simplifying the calculation. However, mostly it is due to the fact that the actual experimental conditions were not available and, therefore, not replicable analytically.

The use of appropriately shaped nylon profiles instead of mortar allows for a certain decrease of the U value of glass block dry-assembled panels compared with that of glass block walls wet-assembled with traditional mortar (due to the poor thermal performance of the latter); the variation in U value related to the use of nylon is negligible, if compared with that of glass block walls wet-assembled with lightened mortar, since the thermal performance of the two materials are quite comparable.

However, the use of moulded plastic profiles could be preferred because it allows for faster, and thus less costly, assembly of the panels. Anyway, whatever material it is made of, the supporting structure determines a certain increase in total product U value, which however is very similar to what existing solutions already offer. In this sense, as already highlighted for the thermal belt, an interesting task could be the choice of a different material for the profiles, able to guarantee the same mechanical performance as nylon, but also characterized by better thermal resistance. PLA, for example, seems to fit for this purpose, allowing for a further improvement of the U value compared to nylon. Another possibility could be the redefinition of profiles shape, e.g., to allow for the presence of one or more housing for high insulating materials or cavities that, as already underlined when speaking of the thermal belt, could also be useful for the sake of the technological integration of PV modules.

5.6. Energy Performance Analyses of DSC-integrated Glass Blocks

The multi-software analyses of the energy performance of PV-integrated glass blocks according to the four patented configurations (the so-called "hypotheses of integration" presented in paragraph 4.3.2) have been carried out by considering a dye-sensitized solar device deeply described in literature as for geometry, structure, detailed spectral behavior, and electrical parameters (Wenger et al. 2011).

The main objectives of this study are:

- Determining some of the main thermal, solar, optical and electrical performance parameters related to the glass block integrated with the specific DSC device, according to the four patented configurations;
- Evaluating the relapses of the integration of the DSC device into the glass block, according to these four configurations, on the overall performance of the product;
- Making qualitative and quantitative considerations about advantages and disadvantages relating to each of these four configurations and comparing them among each other.

Such considerations are useful for the subsequent part of the work, which is focused on the individuation of some "optimum combination" by taking into account the results related not only to PV-integrated hypotheses, but also to the thermally optimized glass block configurations, previously introduced and deeply analyzed in this chapter.

5.6.1. Device Characterization

In order to study the energy performance of PV-integrated glass blocks, the dye-sensitized solar module used in the analyses has to be characterized as for thermal, optical, and electrical properties. For the purpose of the study of DSC-integrated glass block, the solar cells/modules, which are sandwich devices composed of several layers, are modeled as unique optical equivalent materials, whose spectral properties result from the combination of the properties of constituent layers.

The main information required for the DSC module regard:

- dimensional characteristics (module dimensions, module configuration, active area, thickness of the glazed substrates, overall thickness);
- density of the composing materials;
- thermal characteristics (conductivity, surface emissivity);
- detailed spectral distribution (and, in particular, spectral transmittance and reflectance in a wavelength range from 280 to 2500 nm corresponding to the total solar radiation);
- STC conversion efficiency (%).

Having defined for a DSC module all the above data — that can be derived from literature, experimental measures on DSC samples and/or module manufacturers — the analyses of the energy performance of the DSC-integrated glass blocks can be undertaken according to the multi-software methodology defined in this work and introduced at the beginning of this chapter. When some of the above-defined parameters are not given, some assumptions turn out necessary to perform the analyses.

5.6.1.1. Wenger's DSC module

The DSC device deeply discussed by Wenger et al. (2011) was added as a new glazing material and used as input for the simulations. The device is characterized by 6 layers as shown in Figure 5.8.

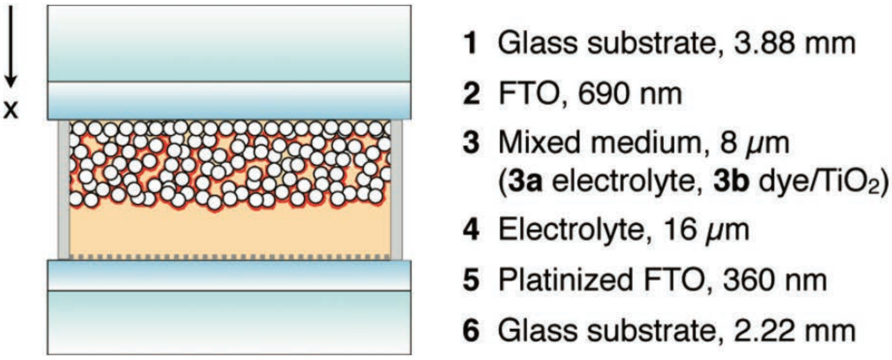
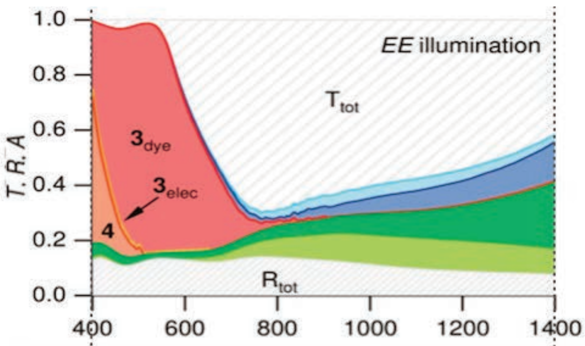


Figure 5.8 - Structure of Wenger's dye-sensitized solar cell depicting the six layers and related thicknesses (Wenger et al., 2011)

The device was also used as input in the optical analyses related to BIPV glass block in previous works (Corrao et al. 2014). The spectral behaviour of this DSC device, in a range of wavelengths from 400-1400 nm, was illustrated in a graph (Figure 5.9), from which required data, i.e. spectral transmittance and reflectance, were extracted[31]. Since the optical characteristics of the DSC module used were only given at a wavelength range of between 400-1400 nm, it was necessary to make an assumption about the remaining part of the solar spectrum (ranging from 280-2500 nm). The values of absorption, reflection and transmission in the excluded ranges, from 280-400 nm and 1400-2500 nm, were considered constant and equal to the value corresponding to 400 nm and 1400 nm respectively.



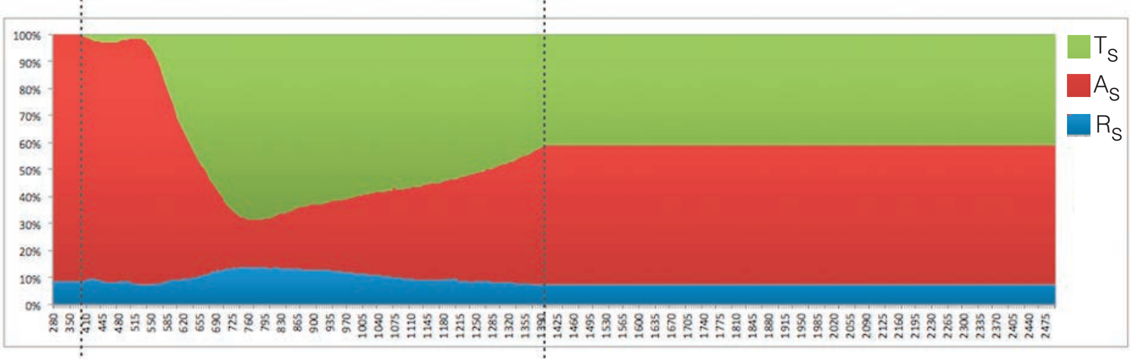


Figure 5.9 - *(left)* Graph showing the spectral distribution of Wenger's DSC at wavelengths from 400-1400 nm (Wenger et al., 2011);

(bottom) Graph showing the spectral transmittance (T), reflectance (R), and absorptance (A) of Wenger's DSC at wavelengths from 400-1400 nm and assumptions for the remaining part of the solar spectrum

This assumption should not affect the results in a significant way, since the amount of energy corresponding to the excluded ranges is only about 10% of the total energy of the whole solar spectrum (Figure 5.10). Moreover, all considerations related to the visible part of the spectrum are not affected at all by this assumption.

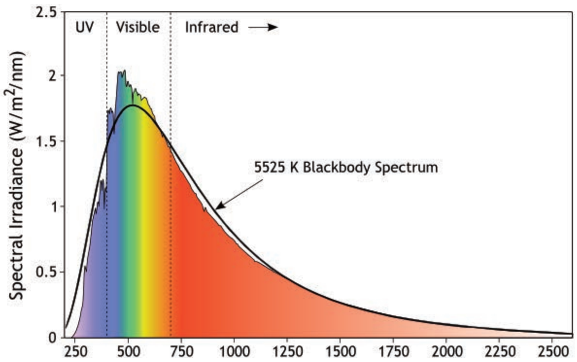


Figure 5.10 - Distribution of the Solar Energy Spectrum in the wavelength range from 250 to 2500 nm (http://qdl.scs-inc.us)

Another assumption was made for the characterization of DSC device thermal conductivity, which was assumed equal to the thermal conductivity of glass (1 W/mK). The global thickness of the device is 6.125 mm and, in particular, glazed substrates (3.88+2.22 mm = 6 mm) characterize approximately 98% of the thickness of the device. Therefore, neither this assumption is expected to affect the results in a significant way, since the thickness of the DSC active layer is negligible compared to the thickness of the two glass substrates of the solar devices. It might have had some influence on the results only if the DSC active layer conductivity was significantly lower than that of glass, which is very unlikely considering the conductivity values of some of the DSC components. Same reasoning is valid for the assessment of module density, which has been assumed equal to that of glass.

As for the surface emissivity of DSC module, it coincides with the emissivity of the glazed surfaces that constitute the substrates of the device and is equal to 0.837.

The efficiency of the device, as reported in the Wenger et al. (2011), is equal to 7.6%.

After having collected the data related to it, Wenger's DSC device can now be used as a new material in the energy performance simulations.

5.6.2. Calculation of the U value of PV-integrated configurations by means of Comsol

The evaluation of the thermal transmittance (U value) of the DSC-integrated glass blocks was made according to the standard EN 673, by simulating a single environmental condition involving internal/external temperature difference without direct solar radiation. This means that, for the calculation of the U value, the PV-integrated glass block is assessed while the solar module is not irradiated and subsequently while it is not working.

Hence, simply by inputting the thermal properties of the interlayer used for gluing the solar module to the surface of the glass shell and the DSC module itself, it is possible to obtain the U value of the PV-integrated configurations in non-operating conditions, simply by repeating the same procedures described in paragraph 5.5.1.

The interlayer used for these analyses is a commercial Polyvinyl Butyral (PVB) film (Butacite®)[32] with the following properties:

- Thickness: 0.38 mm (15 mil);
- Density (ρ): 1070 kg/m^3;
- Conductivity (λ): 0.378 W/mK.

Firstly, the four patented PV-integrated configuration, which basically correspond to all possible positions of the module inside the glass block, were analysed.

As for the U values, the different configuration, simulated with Comsol, provide different results, which are reported in Table 5.9.

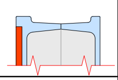
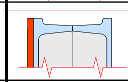
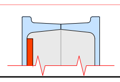
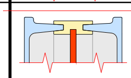
				Thickness (cm)	Nr. of Cavities	Cavity Filling	Thermal Break	Thermal Belt	Sheet Material	2015		λeq	
										2D	3D	2D	3D
PV Patented Hypotheses	V	1		8,6	1	Vacuum	-	-	-	2,4	2,6	0,352	0,390
	A			8,6	1	Air	-	-	-	2,9	2,9	0,474	0,492
	V	2		8,6	1	Vacuum	-	-	-	2,4	2,6	0,353	0,389
	A			8,6	1	Air	-	-	-	2,9	2,9	0,475	0,491
	V	3		8	1	Vacuum	-	-	-	2,5	2,7	0,350	0,385
	A			8	1	Air	-	-	-	3,0	3,0	0,472	0,486
	V	4		10	2	Vacuum	Nylon	Nylon	DSSC	1,7	1,6	0,238	0,228
	A			10	2	Air	Nylon	Nylon	DSSC	2,0	1,7	0,293	0,248

Table 5.9 - U and equivalent conductivity values of the 4 patented Hypotheses

The U values of Configurations 1 and 2 are quite close and, rounded to the decimal, coincide. They are equal to: 2.9 W/m^{2}K, when the glass block cavity is filled with air, and 2.6 W/m^{2}K, when the glass block cavity is evacuated. In fact, in Configurations 1 and 2, whose global thickness is 8.65 mm, a glazed layer, that is the non-operating DSC module, and the Butacite® film are added to the standard 80-mm thick glass block. U values do not change significantly with respect to corresponding configurations without PV, both in air-filled and evacuated situations (see Table 5.4, rows 1-2).

Configuration 3 includes the insertion of the Butacite® film and DSC module inside the glass block, on the internal face of the sun-facing glass shell. This operation provides a slight increase in the resulting U value compared to Configurations 1 and 2. This is probably due to the 6.5 mm reduction of the thickness of the internal cavity and of the whole glass block (80 mm), translating into a lower resistance to heat conduction for Configuration 3. The best insulation is provided by Configuration 4, which is 20 mm thicker than the others and presents the nylon thermal belt. However, most importantly it is where the internal cavity is subdivided into two chambers by the DSC module itself.

As it is possible to see from the results of the analyses, the DSC module itself does not have a significant effect on global product U value, since for U value calculation a winter night condition is considered. It "simply" behaves as an added glazed layer, placed in different positions inside the glass block, since its conductivity is equal to that of glass.

Among the four hypotheses, the only efficient configuration as for the thermal insulation is Configuration 4, which could instead present some issues related to PV productivity due to the possibly partial shading of the module, when placed inside the glass block. Indeed, besides the U value, several other parameters (i.e. g-value, energy production, visible transmittance, temperature reached by the module) and other aspects (such as ease of manufacturing, resistance to degradation and atmospheric agents) must also be taken into consideration in order to choose the best performing configuration.

Other configurations must be analyzed, in order to define the best combination of thermal insulation, electricity production, solar gain, optical performance, and so on. The analyses that will be described in the following paragraphs are aimed to provide such parameters and to outline a more comprehensive overview of the energy performance of the four DSC-integrated glass block "hypotheses".

5.6.3. Thermal and Optical Analyses by means of WINDOW and Optics

This paragraph will discuss in detail the analyses executed with WINDOW software for the evaluation of the thermal and optical performance of the four patented configurations of PV-integrated glass block. The specific properties calculated are:

- the total solar energy transmittance (g-value or SHGC, Solar Heat Gain Coefficient);
- the solar and visible Transmittance (T_{sol} and T_{vis}).

The software also provides the temperature distribution on each of the layers that compose the glazing system.

Actually, in WINDOW glazing systems are simplified as two-dimensional models: each glazed subcomponent is considered as a layer, while the space between each of these layers is filled with gas. For each of the thermal and optical properties computed by the software, only one value, corresponding to the centre of the glazed system, is provided. This simplification, which is more easily suited to flat glass, has the downside of not taking into account the actual three-dimensional shape of the glass block (190x190x80 mm), provided with a glazed border, but rather considers it as a mere sequence of glazed layers and gas spaces[33]. This choice, despite not enabling a complete evaluation of glass block performance, is still sufficient for comparison with other glazing products and for the understanding of the behavior of the so-called vision area that is the part characterized by the two flat surfaces of the glass shells and represents approximately 70% of the surface of the product[34].

The main advantage of WINDOW is that it easily simulates different configurations, correlating the results in terms of both thermal and optical properties, allowing for qualitative and quantitative considerations on advantages and disadvantages of the analyzed configurations. In actual fact, WINDOW is also able to introduce edge and frame properties that could be useful to approximate the shape of glass block configurations[35].

Some considerations on PV production can also be made, taking into account the optical absorption of the DSC layer and the PV active area.

Analyses started from the four “Hypotheses” and, subsequently, they were extended to some new “optimized” configurations (later presented and discussed in par 5.10).

5.6.3.1. Optical analysis of Wenger’s DSC

In order to analyze the PV-integrated glass block, Wenger’s DSC device (presented in paragraph 5.6.1.1) was added as a new glazing material through the use of Optics software (LBNL, 2013) that enables the analysis of optical properties of glazing systems, and was used as input for the simulations.

The data related to the spectral behaviour of this DSC device were inserted in a text file set with the format of the spectral data files listed in the International Glazing DataBase (IGDB)[36]. Then, Wenger’s DSC glazing was created by importing this text file in Optics User Database. As an example, the first page of Wenger’s DSC text file for importation into Optics software is reported in Figure 5.11. Once the importation is completed, Wenger’s DSC glazing can be utilized as a glazed layer in WINDOW as well.

Starting from detailed spectral data, with Optics software it is possible to obtain global optical properties (visible transmittance, solar transmittance, information related to color coordinates and color rendering index) of any kind of glazing system, according to different spectra and standards. In this case, the standard EN 410 was used as reference. The properties that characterize Wenger’s DSC thermal and optical behavior are reported below, in Table 5.10.

```
{ Units, Wavelength Units } SI Microns
{ Thickness } 6.125
{ Conductivity } 1.000
{ IR Transmittance } TIR=0.000
{ Emissivity, front back } Emis= 0.840 0.840
{ }
{ Product Name: Wenger }
{ Manufacturer: Wenger }
{ Type: Monolithic }
{ Material: Glass }
{ Appearance: Red }
{ Acceptance: # }
{ NFRC ID: 40002 }
0.280    0.0000    0.0893    0.0893
0.285    0.0000    0.0893    0.0893
0.290    0.0000    0.0893    0.0893
0.295    0.0000    0.0893    0.0893
0.300    0.0000    0.0893    0.0893
0.305    0.0000    0.0893    0.0893
0.310    0.0000    0.0893    0.0893
0.315    0.0000    0.0893    0.0893
0.320    0.0000    0.0893    0.0893
0.325    0.0000    0.0893    0.0893
0.330    0.0000    0.0893    0.0893
0.335    0.0000    0.0893    0.0893
0.340    0.0000    0.0893    0.0893
0.345    0.0000    0.0893    0.0893
0.350    0.0000    0.0893    0.0893
0.355    0.0000    0.0893    0.0893
0.360    0.0000    0.0893    0.0893
0.365    0.0000    0.0893    0.0893
0.370    0.0000    0.0893    0.0893
0.375    0.0000    0.0893    0.0893
0.380    0.0000    0.0893    0.0893
0.385    0.0000    0.0893    0.0893
0.390    0.0000    0.0893    0.0893
0.395    0.0000    0.0893    0.0893
0.400    0.0000    0.0893    0.0893
0.405    0.0040    0.0893    0.0893
0.410    0.0079    0.0909    0.0909
0.415    0.0103    0.0933    0.0933
0.420    0.0127    0.0949    0.0949
0.425    0.0169    0.0952    0.0952
0.430    0.0210    0.0952    0.0952
0.435    0.0226    0.0937    0.0937
0.440    0.0242    0.0907    0.0907
0.445    0.0265    0.0893    0.0893
0.450    0.0288    0.0853    0.0853
0.455    0.0293    0.0835    0.0835
0.460    0.0298    0.0817    0.0817
0.465    0.0296    0.0813    0.0813
0.470    0.0295    0.0813    0.0813
0.475    0.0276    0.0813    0.0813
0.480    0.0258    0.0831    0.0831
```

Figure 5.11 - First page of Wenger’s DSC text file for importation into Optics software

	Wenger’s DSC
Thickness (mm)	6.125
Thermal Conductivity (W/mK)	1.000
Solar Transmittance	0.357
Solar Reflectance, front	0.100
Solar Reflectance, back	0.100
Visible Transmittance	0.128
Visible Reflectance, front	0.084
Visible Reflectance, back	0.084
Infrared Transmittance, Tir	0.000
Emissivity, front	0.837
Emissivity, back	0.837

Table 5.10 - Physical, optical and thermal properties of Wenger’s DSC module

The module is characterized by a low value of visible transmittance (12.8%). Indeed, it absorbs mostly in the visible range that is also the part of the solar spectrum with the highest energy amount (which translates into higher efficiency of the device). In the solar range, instead, the global transmittance goes up since the device is more transparent to infrared radiation than to visible one.

The device is a small-scale lab sample, optimized as for the electrical properties. The whole area of the device is active and its conversion efficiency is 7.6%.

In the scale-up for the integration with the glass block, optical properties are expected to maintain unvaried, whereas a sensible decrease in the electrical performance is expected; indeed, lab cells are generally highly optimized devices, whereas scaled-up commercial products are characterized by manufacturing defects, losses due to the interconnections of the different cells to form modules and therefore a drop in the performance (which is not easy to predict or quantify exactly).

Furthermore, for electric productivity purposes, scaled-up devices (for commercial applications) are characterized by the presence of inactive spaces between one cell and the other. This leads to a further conversion efficiency decrease, which, for example, can be quantified equal to 25%, if we assume 75% active area percentage.

After having defined the characteristics of the DSC device and input them into Optics software, the module is ready to be imported as a glazing layer into WINDOW software as well.

5.6.3.2. Creation of laminates

Since putting two glazed layers directly next to each other is not possible with WINDOW, which instead automatically inserts a gaseous space between them, new laminates were created by putting together the DSC module and the glazed layer, that in the models represents one of the glass shells, through the insertion of a PVB film (or interlayer, that is the term used in Optics) in the middle. In particular, DSC module faces external environment to simulate Configurations 1 and 2; it faces internal environment to simulate Configuration 3. In Configuration 4, it is not needed to create any laminate and the module is imported in WINDOW as it is.

The same procedure can be repeated for any kinds of DSC modules, for which spectral transmittance and reflectance data are available.

	DSC/PVB/Glass Laminate
Thickness (mm)	11.165
Thermal Conductivity (W/mK)	1.000
Solar Transmittance	0.323
Solar Reflectance, front	0.170
Solar Reflectance, back	0.170
Visible Transmittance	0.129
Visible Reflectance, front	0.082
Visible Reflectance, back	0.082
Infrared Transmittance, Tir	0.000
Emissivity, front	0.837
Emissivity, back	0.837

Table 5.11 - Properties of Wenger's DSC/PVB/Glass laminate

5.6.4. WINDOW analyses of DSC-integrated Glass Blocks

For the definition in WINDOW of the glazing system, according to the four PV-integrated configurations, the following information need to be provided:

- *number of glazing layers* (which also determines the number of cavities, which are automatically interposed between two glazing layers, e.g. single glazing-no cavity; double glazing-one cavity; triple glazing-two cavities…);
- *type of glazing layers* (which can either be selected within IGDB or imported from the Optics User Database);
- *thickness of the cavity/ies and characteristics of the gas filling*;
- *dimension of the glazing system* (the thickness is automatically calculated from the above information, whereas the height of the glazing system needs to be inserted by the user). In the case of the glass block the height of the system is considered equal to the height of glass block cavity (i.e. the vision area, around 160 mm in the case of Q19 glass block).

A screenshot of the software interface in the glazing system section is reported in Figure 5.12, where, in particular, a glazing system corresponding to the standard glass block is illustrated.

For the analysis of thermal and optical performance of the different glass block configurations, some of which are characterized by 70 mm evacuated cavities inside the product, it was also necessary to create a new gaseous material, called "Vacuum Trick", since WINDOW does not consider vacuum spaces that are thicker than 10 mm. "Vacuum Trick" is described as a gas with nearly zero density and thermal conductivity. Some simulations were performed in order to assess the reliability of the results coming from this assumption.

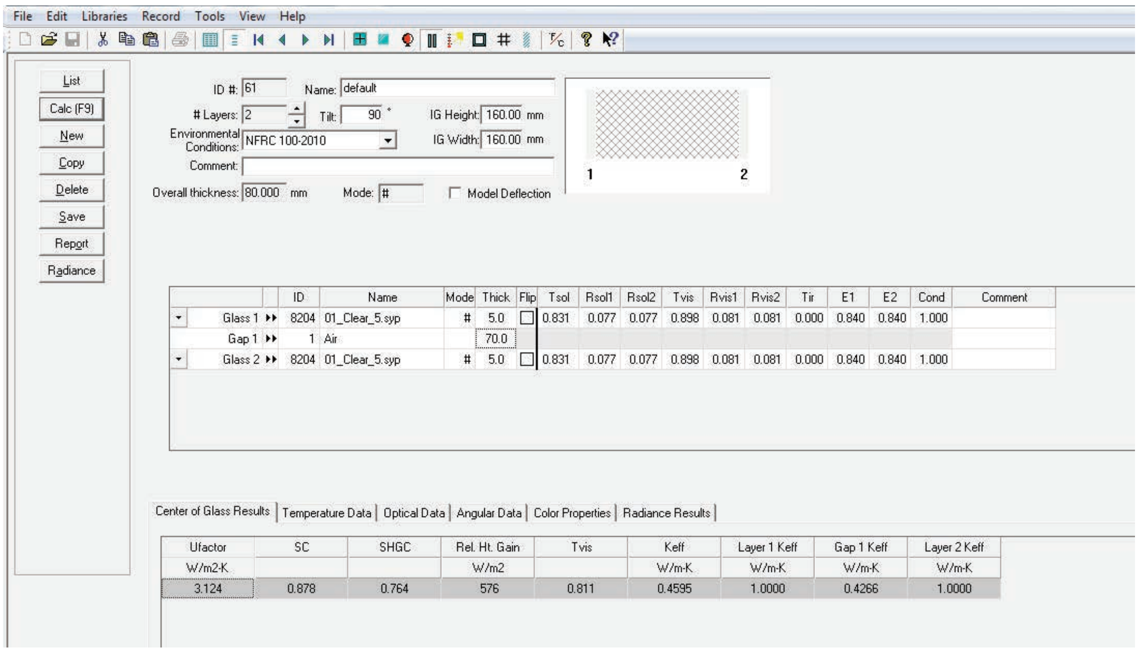


Figure 5.12 - Example of a screenshot of the WINDOW software interface

Speaking of the analyses, Configurations 1 and 2 only differ on the percentage of the DSC module area on the external surface of the glass block. For this reason, they have been considered equivalent for the purposes of thermal and optical performance calculation through WINDOW. At present, indeed, what happens in the glass block boundary is not taken into account[37]. In the case of Configuration 4, the analysis also neglected the presence of the thermal belt and thus also its effects on the energy performance of the product.

The centre-of-the-glazing SHGC and U value are determined by using the environmental conditions indicated in Table 5.12, corresponding respectively to conditions in extreme summer (with sun striking perpendicularly on the surface of the glazing systems) and winter, without direct solar radiation (according to NFRC 100:2010).

Environmental Conditions from standard NFRC 100-2010	
SHGC	U value
Inside air temperature: T_{in} = 24°C	Inside air temperature: T_{in} = 21°C
Outside air temperature: T_{out} = 32°C	Outside air temperature: T_{out} = -18°C
Outside wind speed: V = 2.75 m/s	Outside wind speed: V = 6.50 m/s
Effective room temperature: $T_{rm,in} = T_{in}$	Effective room temperature: $T_{rm,in} = T_{in}$
Effective sky temperature: $T_{rm,out} = T_{out}$	Effective sky temperature: $T_{rm,out} = T_{out}$
Direct Solar Radiation: 783 W/m^2	Direct Solar Radiation: 0 W/m^2

Table 5.12 - WINDOW Environmental Conditions

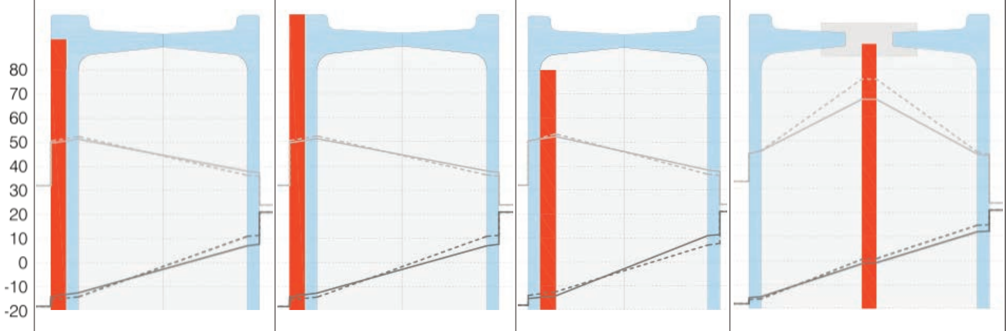
The software provides the temperature distribution associated with the two above environmental conditions for each of the analyzed configurations, allowing for further considerations on their energy performance. However, as already underlined, the characteristics of DSC module do not produce a significant change in winter performance, whereas in summer condition (SHGC calculation) they do.

5.6.5. Discussion of the Results

The results of the analyses of the four PV-integrated glass block configurations, based on the use of Wenger's DSC module, are reported in Table 5.13, where they are coupled with Comsol Multiphysics results, calculated in both 2D and 3D environments and widely discussed in paragraph 5.6.2. The border of the glass block is accounted for in Comsol simulations only.

The solar heat gain coefficient (SHGC), visible transmittance (T_{vis}), solar transmittance (T_{sol}) and the temperature distribution (illustrated in a cross-section of each glass block configuration), referred to the vision area of the product, were obtained from WINDOW. For the sake of completeness, the g-value calculated according to the environmental conditions and procedures indicated in the EN 410 is reported as well[38].

	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
Module area %	81%		94%		58%		66%	
Thickness (mm)	86.5		86.5		80		100	
U_{1D} (W/m²K)	2.2	2.7	2.2	2.7	2.2	2.7	1.4	1.7
U_{2D} (W/m²K)	2.4	2.9	2.4	2.9	2.5	3.0	1.7	1.9
U_{3D} (W/m²K)	2.6	2.9	2.6	2.9	2.7	3.0	1.6	1.7
SHGC	37.00%	38.60%	37.00%	38.60%	37.40%	39.00%	46.70%	46.50%
g-value	34.50%	35.10%	34.50%	35.10%	34.70%	35.30%	45.30%	45.00%
T_{vis}	11.47%		11.47%		11.44%		10.21%	
T_{sol}	26.55%		26.55%		26.50%		24.19%	
DSC absorption	47.72%		47.72%		40.85%		40.85%	



LEGEND	
NFRC 100-2010 (SHGC), air-filled	NFRC 300-2010 (U value), air-filled
NFRC 100-2010 (SHGC), evacuated	NFRC 300-2010 (U value), evacuated
DSC	Glass

Table 5.13 - Summary of Results of WINDOW and Comsol analyses on DSC-integrated glass blocks

Despite having the highest insulation in the winter season, as calculated in winter conditions without sun (see paragraph 5.6.2), Configuration 4 also shows the highest SHGC, that is the rate of heat transfer depending upon both directly transmitted solar gain and absorbed (then transmitted) solar gain.

As shown in Table 5.13, the highest SHGC is not corresponded by to highest solar transmittance, but rather it is due to the high temperatures reached inside the glass block (over 70 °C, the highest among the configurations tested). Such temperatures are due to the solar absorption and warming of DSC module, which is not ventilated and is insulated from the external environment, especially when the cavity is evacuated. This can represent a problem because such high temperatures can generate situations of summer discomfort, particularly in warm climates, as well as the thermal stresses on the DSC module with potential negative effects on its durability and electricity production. On the other hand, the way to exploit this heat storage in cold climates in order to improve indoor comfort, could be a matter for further investigations.

However, it should be noted that DSC performance endure high operating temperatures significantly better than first- and second-generation PV technologies. Indeed, the temperature coefficient, characterizing the percentage loss of efficiency per 1°C temperature increase, is the lowest of the PV technologies, equal to -0.005 %/°C against -0.45 %/°C for crystalline silicon (Heinstein et al. 2013).

In Configurations 1, 2 and 3, where the laminate constituted by the DSC module and the face of the glass shell is more or less in direct contact with the external environment, better ventilation is provided and significantly lower temperatures on the surface of the DSC module occur. However the surface of the glass shell that faces the internal environment (24 °C) presents temperatures between 35-40 °C, according to the four configurations: these values are perfectly comparable with the ones for existing glazing of varying complexity, as it is possible to see, for example, in Table 5.14 showing thickness, U value and internal glass temperature of different glazing systems from IGDB, simulated in WINDOW according to the same standard environmental conditions.

Glazing system	Thickness (mm)	U value (W/m^2K)	Internal glass surface Temperature (°C)
Single Clear Glass	3.05	5.9	32.3
Double Clear Glass, Air	23.4 [5.7+12+5.7]	2.7	36.3
Double Low-e, Air	21.6 [3.2low-e+12.7+5.7]	1.7	32.0
Double Clear, Argon	18.7 [3+12.7+3]	2.6	33.0
Triple Clear, Air	42.5 [5.7+12.7+5.7+12.7+5.7]	1.7	38.4
Double high solar gain low-e, Air	25.9 [4.7low-e+16.5+4.7]	1.9	38.7

Table 5.14 - U value and internal temperature of glazing systems taken from WINDOW glazing system library

In Configurations 1, 2 and 3, in both evacuated and air-filled cases, SHGC is relatively steady around 37-39%, not taking into account the glass block border and effective DSC module area. Their U values need to be optimized too and, in this sense, thermally optimized glass block configurations can be merged with DSC-integrated configurations, in order to further optimize the performance of the product.

All configurations show low values of visible transmittance, close to 10%. This is due to the low transparency of the DSC device used for the simulations (T_{vis}=12.8%).

The effects on visible and solar transmittance values of the DSC module area percentage (defined in paragraph 4.3.2), which differ from one configuration to the other, and of the glazed border, can be qualitatively predicted in this phase; significant changes are not expected to occur compared to the configurations already simulated with WINDOW. Visible and solar transmittance in Configurations 1 and 2 will probably decrease by some percentage points, due to the presence of the glazed border and to the wider area covered by DSC, with respect to the configurations assessed by WINDOW. In particular, Configuration 2 will have a bigger decrease than Configuration 1, having a wider DSC module area percentage. However, Configuration 3 should have slightly higher visible and solar transmittance, since the area covered by DSC is smaller than that accounted for in WINDOW. Although in Configuration 4 the DSC module area does not change from that simulated in WINDOW, this PV-integrated glass block configuration will likely suffer from the highest decrease. This is because the border (that is not accounted in WINDOW) has a completely opaque part, i.e. the thermal belt. These considerations will be verified by the simulations carried out by means of Zemax and described in paragraph 5.7.

In order to make a preliminary evaluation of the configuration with the highest energy production, absorption values of the DSC layer can be taken into account. DSC absorption in Configurations 3 and 4 is identical and equal to 40.85%. This is due to the fact that sun rays are assumed to strike the surface of the glazing systems perpendicularly and thus the partial shading, which can have important effects in Configuration 4 depending on the position of the sun, is not taken into consideration. The active area in both cases corresponds only to a part of the total surface of the glass block and, in particular, in Configurations 3 and 4 it is about 58% and 66% respectively.

DSC absorption is equal to 47.72% in both Configurations 1 and 2, which, as has already been said, are considered identical for the purposes of WINDOW analyses and only differ in the amount of glass block surface that is covered with DSC (81% and 94% respectively). Having said that, Configuration 2 should be the one producing the highest amount of electricity[39]. Also as regards the estimation of the electrical power of the DSC-integrated glass blocks according to the four "Hypotheses" of integration, a more detailed study has been carried out with the support of the optical design software Zemax and it can be found later in this chapter, at paragraph 5.7.2.

5.6.6. Accounting for the Active Area

As already underlined, all configurations show low values of solar and visible transmittance, due to the optical characteristics of the module used for the simulations. As the discussion provided on this third-generation technology in Chapter 2, at paragraph 2.3.3.2., DSC modules can easily be designed with higher transparency value, although often this is linked with a certain reduction in the conversion efficiency.

However, it should also be noted that, in the DSC module used for the above-reported analyses, the whole area of DSC module is considered as active while, in actual fact, the typical configuration of DSC modules is not fully covered with solar cells; indeed, for electric productivity purposes, and in particular to avoid internal resistance losses, DSC modules are normally characterized by a series of rectangular narrow cells with highly transparent non-PV spaces between them. This means that an increase in devices' solar and visible transmittance as well as a decrease in STC power density can be expected.

An active area percentage (AA%) can be defined in each DSC module: it is represented by the ratio of the active area (i.e. the surface effectively occupied by dye-sensitized solar cells) and the total area of the module (inactive spaces included), as indicated in the following equation and illustrated in Figure 5.13.

$$AA\% = \frac{A_{active}}{A_{module}} \qquad [12]$$

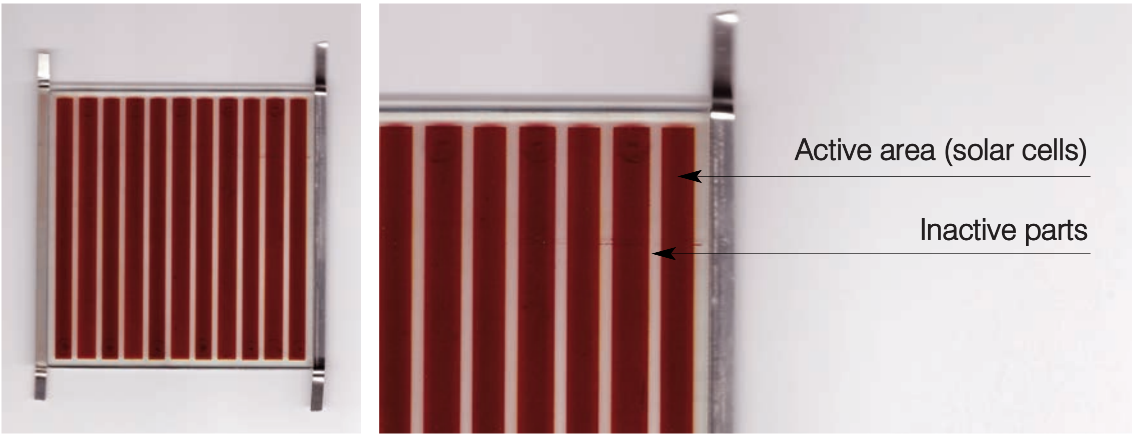


Figure 5.13 - *(left)* picture of a 11W1010 commercial module by Solaronix SA; *(right)* closer view of the module with indication of the active part (solar cells) and of the highly-transparent non-active spaces

The percentage of the active area (AA%) in DSC modules is equal for all PV-integrated glass block configurations and depends only on DSC module characteristics. This value can vary significantly from one manufacturer of DSC modules to the next and basically depends on the module design and manufacturing processes[40]. For example, the Japanese company Sony, also active in the R&D of DSC technology, reached a very high active area percentage (85%) with its DSC modules (Kalyanasundaram et al. 2010); the Swiss DSC manufacturing company Solaronix in 2009 declared an 80% total active area (Meyer et al., 2009). However, there are also different DSC modules configurations (e.g. the 'meander-type' large area module manufactured at Fraunhofer Institute for Solar Energy), where the inactive area is approximately 50% (Kroon et al. 2013). DSC active area percentage in the commercial modules (600x1000x6.5 mm) of the Swiss company Glass2Energy is equal to 76% and can also reach a very high value of 83%; this is possible due to the W-type connection of the cells within the modules produced by the Swiss company and translates into an optimized power density (W/m^2) for the devices. Different design of the module, due to e.g. visual as well as aesthetic requirements, can result in different values of active area percentage and, subsequently, in different optical and electrical performance. In order to take into account the active area percentage and its potential relapses on both PV, thermal and optical performance, an average 75% value was taken as reference in the analyses.

In order to account for the active area percentage of the modules, for each of the DSC devices analyzed, a new DSC module was created in Optics simply by weighting the properties of the DSC module with those of a highly transparent glazing such as the one present in correspondence to inactive spaces between one cell and the other.

Having a look at the typical structure of a W-type DSC module, in correspondence to the inactive area between one cell and the other, we can observe the juxtaposition of three layers:

- a layer of highly transparent TCO glass (glazing coated with a transparent film of a conductive oxide, such as, for example, tin-oxide SnO_2);
- a layer of encapsulant to seal and enclose the cells and keep the two glazed substrates together in the DSC sandwich;
- a layer of highly transparent glass.

In particular, the TCO glass[41] deeply analyzed by Von Rottkay and Rubin (1996) was used for the evaluation. The spectral data (transmittance and reflectance over a spectrum from 290-2500 nm) were extracted from the graph contained in the above cited paper and they were imported in Optics with the already presented methodology. Then, a new laminate was created by putting together a layer of TCO glass (3 mm), highly transparent encapsulant (Butacite®) available in Optics database and highly transparent 3.5 mm thick glass.

The detailed spectral data related to this new laminate, useful to simulate the non active spaces among the cells in the typical striped configuration of DSC module, were obtained from Optics and extracted in the form of a text file. Subsequently, the detailed spectral properties (transmittance and reflectance) of the active and non active part in DSC module were weighted considering 75% active area percentage for the DSC module.

In the following table, main optical properties related to the Wenger's DSC module with 75% active area and 25% highly transparent non-active area are reported and compared with those of the wholly active Wenger's DSC device.

	Wenger's DSC (100% active area)	Wenger's DSC (75% active area)
Thickness (mm)	6.125	
Thermal Conductivity (W/mK)	1.000	
Solar Transmittance	0.357	0.420
Solar Reflectance, front	0.100	0.112
Solar Reflectance, back	0.100	0.112
Visible Transmittance	0.128	0.294
Visible Reflectance, front	0.084	0.085
Visible Reflectance, back	0.084	0.085
Colour Transmittance (CIE L*, a*, b*)		
Colour Rendering Index	0.98	59.53
Conversion Efficiency	7.6%	5.7%

Table 5.15 - Characteristics of Wenger's DSC module in 100%-active and 75%-active area configurations

As expected, the light transmission performance of the newly created DSC module (with 75% active area percentage) significantly increased compared to the “original” DSC device (without any inactive spaces): the visible transmittance goes from 12.8% up to 29.4%. This is a very interesting aspect to consider, especially if we are dealing with building integrated applications. Solar transmittance, instead, does not increase as significantly, going from 35.7% to 42%. We can outline an improvement in the optical performance of the device related to the accounting of the active area percentage, whereas this obviously leads to a decrease in the PV performance due to the reduction of the active portion of the device per unit area.

Once the Wenger’s DSC 75%-active module has been defined in Optics, it can be imported as a glazing layer in WINDOW to perform the analyses of PV-integrated configurations.

5.6.6.1. Discussion of the Results

The results of the analyses of the four glass block configurations, integrated with Wenger’s DSC 75%-active module, are reported in Table 5.16.

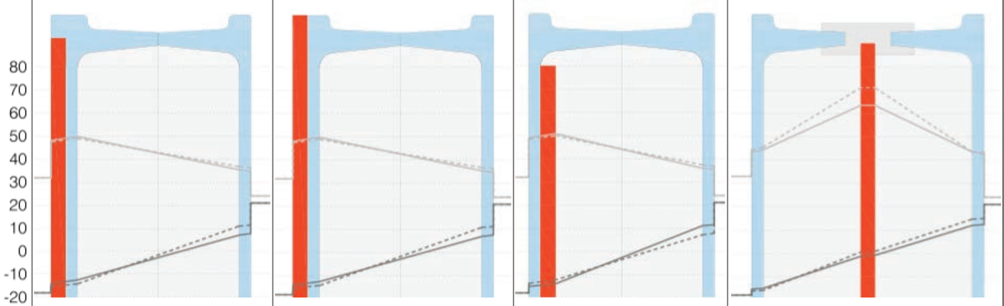
	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
Module area %	81%		94%		58%		66%	
Thickness (mm)	86.5		86.5		80		100	
U_{1D} (W/m^{2}K)	2.2	2.7	2.2	2.7	2.2	2.7	1.4	1.7
U_{2D} (W/m^{2}K)	2.4	2.9	2.4	2.9	2.5	3.0	1.7	1.9
U_{3D} (W/m^{2}K)	2.6	2.9	2.6	2.9	2.7	3.0	1.6	1.7
SHGC	42.80%	44.40%	42.80%	44.40%	43.20%	44.90%	52.10%	51.90%
g-value	43.80%	44.30%	43.80%	44.30%	44.10%	44.60%	53.00%	52.70%
T_{vis}	26.61%		26.61%		26.55%		23.80%	
T_{sol}	32.08%		32.08%		32.03%		29.34%	
								
LEGEND	NFRC 100-2010 (SHGC), air-filled NFRC 100-2010 (SHGC), evacuated DSC				NFRC 300-2010 (U value), air-filled NFRC 300-2010 (U value), evacuated Glass			

Table 5.16 - Summary of the results of WINDOW and Comsol Analyses (U value) on DSC-integrated glass block configurations (relating to Wenger’s DSC with 75% active area)

Results show a significant increase (of around 15 points) in glass block visible transmittance, a certain growth in solar transmittance (of around 5 points), whereas a decrease in energy absorption of the DSC (with directly proportional decrease in the expected electricity production, also due to active area reduction). Also the temperatures recorded on glass block surfaces decrease, whereas U value remains unvaried.

As for the total solar energy transmittance, expressed by the SHGC, a slight increase can be registered going from 100%-active to 75%-active DSC module. This is due to the higher amount of directly transmitted solar power on the new device with weighted properties, despite also a limited decrease of the solar energy absorption in the different configurations; this also means that a lower warming-up of the product occurs. For instance, the following table takes Configuration 4 as an example, since it is that were this phenomenon is more relevant and where it is possible to better note that the increase in T_{sol} does not result into a corresponding increase in SHGC, due to reduction in the secondary heat transfer coefficient.

CONFIGURATION 4	SHGC = T_{sol} + q_i	Direct solar transmittance (T_{sol})	Secondary heat transfer coefficient (q_i)
100%-active DSC	49.10%	24.10%	25.00%
75%-active DSC	51.90% (+1.80%)	29.34% (+5.25%)	21.56% (- 3.44%)

Table 5.17 - Analysis of the components of SHGC in Configuration 4, considering both 100%- and 75%-active DSC

The results shown in Table 5.16 come from an approximation — that is weighing the properties of subcomponents according to their respective area — that should also be verified experimentally[42], but that is also of relevance to consider, since the whole module area as active is a thing that practically never occurs (at least, at present[43]).

These results are also useful to understand the link between all the studied parameters (transparency, solar factor, electricity production, temperature in the device) and the active area percentage. More in general, such approach could allow to evaluate preliminarily the effects, on the optical and solar performance of the DSC-integrated glass blocks, of a variation in the active area percentage and, more in general, in the configuration of the integrated module. For example, a certain value of active area percentage, deriving from a specific layout of the solar device (in terms of e.g. cells disposition, thickness and interdistance), could be chosen in order to adapt to the specific light transmission requirements of the envelope of a building, similarly to what occurs in traditional crystalline silicon panels. It should be however underlined that in the DSC technology, differently than in first- and second-generation technologies, diversified values of transparency can be achieved by intervening on DSC module nanostructure, without giving up on the active area.

For a more detailed reading and for a comparison of the results of WINDOW and Comsol analyses regarding both 100%-active and 75%-active Wenger's DSC modules, Table 5A.1 in the appendix. It contains all parameters obtained from the above analyses.

5.7. Zemax Analyses of Solar, Optical and Electrical Performance

In order to deeply understand the optical behavior of the PV-integrated glass block, further analyses were necessary by using the ray-tracing commercial software Zemax (Radiant Zemax LLC, 2009), which simulates the propagation of rays through an optical system and the effects of the presence of different objects (such as simple and aspheric lenses, mirrors, diffractive elements). By means of Zemax, also the three-dimensional shape of the building product was accounted for, with the aim to fully describe the optical behavior of the product in the different configurations, considering also the contributions related to the thermal belt and the glazed borders as well as of the support structure made of plastic profiles. De facto, as underlined in other works (Zinzi et al. 2000), for more accurate results, it is important to consider the optical parameters close to the edge of the glass block. This study was also of relevance for the evaluation of the electrical power related to each of the glass block configurations defined. The analyses with Zemax were useful also to verify, some of the results that came from WINDOW software. This could be very important, especially in a first phase characterized by the absence of experimental data related to the DSC-integrated glass block.

5.7.1. Setting-out of the simulations

The characteristics of Zemax and its functioning have already been studied, described and verified in other works (Calabrò 2014, Di Maggio 2014), which confirmed — also through analytical calculation[44] — the reliability of this software for the simulation of the studied product. The software was used in the non-sequential mode (enabling to set three-dimensional models and import CAD files).

First of all, in order to simulate the optical response of the DSC-integrated glass block in the four hypotheses, it has been necessary to define geometry of the objects to be analyzed: the three-dimensional CAD model of each of the four different DSC-integrated glass block configurations was imported and positioned.

Secondly, it was necessary to define the optical properties of each material composing the system. Zemax is also characterized by a DataBase of materials (mainly glazing) that can be assigned to the given objects; alternatively, starting from detailed spectral data, new materials can be set and assigned to the objects in the model. This is what was done in this case, for the characterization of both the glass composing the glass block and the DSC device. In particular, the spectral transmittance $\tau(\lambda)$, reflectance $\rho(\lambda)$ and absorptance $\alpha(\lambda)$ (that are linked among each others because of the Energy Conservation law, equation [2]) as well as the corresponding refractive index *n* and extinction coefficient *k* of each layer of the system were defined, taking into account wavelengths ranging from 280 to 2500 nm[45].

However, it must be noted that, apart from the spectral refractive index of each material, Zemax does not require as input data any of the above-mentioned optical properties, which are instead needed to obtain, by simply applying the appropriate laws of optics, a parameter indicated by the software as $T^*(\lambda)$ correlating reflectance and transmittance[46]. Having defined $T^*(\lambda)$, it was weighted according the selected wavelength ranges and input in the software.

The chosen energy source, which more correctly represents the actual behavior of the sun, is the "Two Angle", enabling the implementation of sun rays perpendicularly to the analyzed object: the program also allows for the definition of the input power of the source (1000 W/m^2) and inserting a number of wavelength intervals with the corresponding weight.

Since the software allows the user to put a limited number of wavelength intervals, the simulations were made by assigning to each of the chosen wavelength ranges a weight proportional to the quantity of energy carried by the ray at each range (as also suggested by the reference standards).

The simulations on the four DSC-integrated configurations were run by setting the direction of sun rays perpendicular to the external surfaces of the glass block.

5.7.2. The Objectives of the Simulations

Results in Zemax can be read on an absorbing film, called "detector". This film is capable, e.g., to provide information about the amount of energy that has passed through the objects, that were intersected by the rays of the chosen light source. The choice of the dimension and, even more importantly, of the position of the detector was fundamental for the correct definition of the searched outputs and different choices have been made, according to what was searched for in each analysis.

Three main situations can be outlined, corresponding to different objectives in the analyses (see Table 5.18):

- *Objective 1. Solar and Visible Transmittance*:
  The detector is placed beyond the glass block and records the power remaining after the glass block has been crossed by the rays of the light source. The dimensions of the detector coincide with those of glass block surface;
- *Objective 2. Electrical Power:*
  The detector is placed right in front of the DSC module in order to record the amount of energy immediately before it strikes module surface. The dimensions of the detector coincide with those of the DSC module. Hence, they change from one configuration to another;
- *Objective 3. Absorption of the layers constituting the glass blocks and g-value:*
  Two simulations are run for each of the glazed layer composing the glass block configuration: in the first, the detector is placed right in front of the layer (whose absorption is intended to be measured); in the second, right beyond it. The dimensions of the detector coincide with those of glass block surface in both simulations.

Each of PV-integrated glass blocks has been simulated in two sets of configurations:

- the first one (indicated as 1.1, 2.1, 3.1, 4.1) is only characterized by glass shells, DSC module and, in the case of Hypothesis 4, the thermal belt;
- the second one (indicated as 1.2, 2.2, 3.2, 4.2) takes also into account glass block support structure made of plastic profiles.

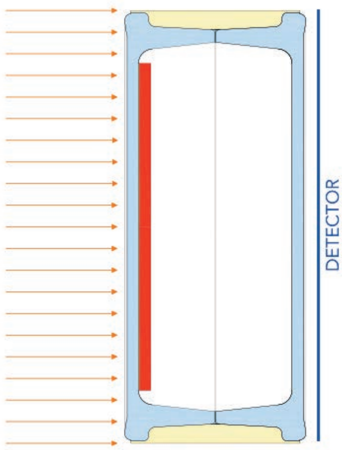
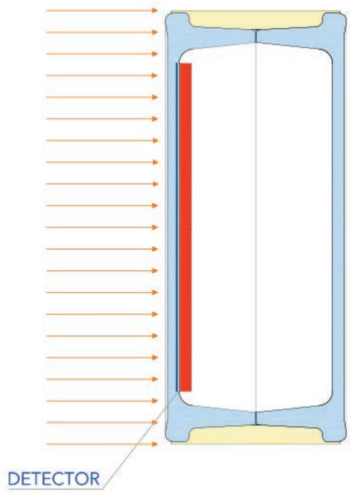
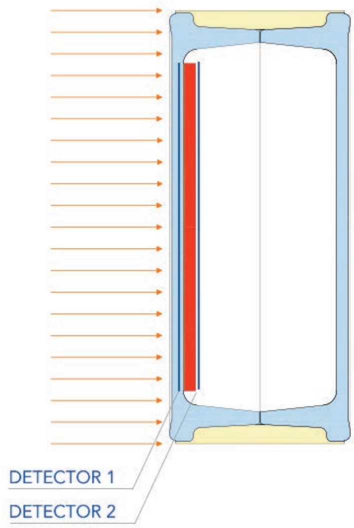
OBJECTIVE 1 Solar and Visible Transmittance	OBJECTIVE 2 Electrical Power	OBJECTIVE 3 Absorption, g-value
		
Position of the detector: beyond the whole glass block	Position of the detector: right in front of the DSC module	Position of the detectors: right in front and right beyond the analysed layer
Dimensions of the detector: coincide with those of glass block surface	Dimensions of the detector: coincide with those of the DSC module	Dimensions of the detectors: in both cases, coincide with those of glass block surface

Table 5.18 - Summary table illustrating the three main objectives of the study and the related setting of the simulations (i.e. detector's position and dimensions)

5.7.2.1. Objective 1: Solar and Visible Transmittance

In order to calculate the direct transmittance both in the solar and visible ranges, respectively T_{sol} and T_{vis}, the detector was placed behind the whole glass block.

As for the solar transmittance, the standard EN 410 defines in detail the spectra according to which light and solar properties of the glazing system should be defined. In particular, it provides the normalized relative spectral distribution of global solar radiation S_λ multiplied by the wavelength interval $\Delta\lambda$, considering the global solar spectrum from 300-2500 nm; this distribution was input in the software in order to define the characteristics of the source.

The detector records the value of the transmitted power across each glass block configuration ($P_{sol,T}$). By dividing this value by the power striking on glass block external surface (which is the power of the chosen source, $P_{sol,0}$), the transmittance of the object is obtained, as in the equation below:

$$T_{sol} = \frac{P_{sol,T}}{P_{sol,0}} \quad [13]$$

This is basically equivalent to applying the definition of the direct solar transmittance provided by the EN 410 standard and expressed, in particular, by the equation [4]. The expression at the numerator is the transmitted solar power: Zemax detector, when placed right behind the glass block, provides one single value that basically corresponds to the result of the summation at the numerator of equation [4]. At the denominator, there is the incident solar power ($P_{sol,0}$), which is defined at the beginning of the simulations when the light source is chosen and its power is input in the software, after being weighted according to the different wavelength intervals that are established in the standard EN 410:2011.

The transmitted solar power, recorded by the detector placed the glass block, together with the power absorbed by each layer (obtained as indicated in paragraph 5.7.2.3.) is also useful to calculate the solar factor (g). This latter is obtained starting from its definition, in accordance to the standard EN 410:2011 (see also paragraph 5.4.2.).

In order to evaluate the transparency of the object as perceived by human eye, the value of transmittance was also calculated in the visible spectrum for wavelengths ranging from 380 to 780 nm. In this case, a different spectral distribution was used, i.e. the normalized relative spectral distribution D_λ of illuminant D_{65} multiplied by the spectral luminous efficiency $V(\lambda)$ and by the wavelength interval $\Delta\lambda$, as indicated in EN 410:2011. The spectral luminous efficiency is an important parameter that takes into account the different responses of human eye to different wavelengths. Similarly to the above equation, the visible transmittance is obtained from the ratio of transmitted power across each glass block configuration ($P_{vis,T}$), as recorded by the detector placed behind the object, by the power striking on glass block external surface coming from the light source, defined according to the above-introduced spectral distribution:

$$T_{vis} = \frac{P_{vis,T}}{P_{vis,0}} \quad [14]$$

The results of the simulations on the four patented configurations, in terms of solar direct transmittance and visible light transmittance, are reported in the Table 5.20, paragraph 5.7.3, where all the results of the different objectives are reported and discussed.

5.7.2.2. Objective 2: Electrical Power

According to what is indicated in Table 5.18, for the assessment of the electric power, the detector was placed right in front of the DSC layer, in order to read the power (I_e) striking the sun-facing surface of the solar device.

The standard solar spectrum used for efficiency measurements of solar cells is defined at AM 1.5 G (global) giving $\varphi=42°$. Also this spectrum is usually given as normalized, so that the integral of the irradiance (the amount of radiant energy received from the sun per unit area and unit time) is 1000 W/m^2. Different values of power were read on the surface of the DSC module in each of the configurations tested. Those values depend on different factors: on the presence - in front of the DSC module - of the glass shell, which reflects and absorbs a part of the energy striking the glass block (in configurations 3 and 4) according to its spectral characteristics; the presence (in configuration 4) of an air cavity between the outer glass shell and the DSC module[47]; the dimensions of the module change from one configuration to another, also imposing a modification in the dimension of the detector and of the power registered by it. The power is calculated through the following equation:

$$P = \mu \cdot I_0 \cdot sen\alpha \cdot A \quad [15]$$

where:

- μ is the photovoltaic conversion efficiency;
- I_0 is the Global Horizontal Irradiance at Standard Test Conditions (1000 W/m^2), striking the surface of the solar device;
- α is the angle of incidence of the solar rays with respect to the cell plane, which, in this case, is considered equal to 90°;
- A is the area of the PV device.

In the present analysis:

- the conversion efficiency μ was assumed equal to 5%[48];
- I_0 is the power striking the outer surface of the glass block. In particular, in Configurations 1 and 2 (where the PV module is directly in contact with the external environment) it coincides with the power striking the surface of the solar device (I_e); in Configurations 3 and 4, the power striking effectively the surface of the solar device (I_e), obtained from Zemax as in Table 5.18, is lower than the initial power striking the glass block (I_0);
- The area of the PV device A is obtained multiplying the glass block area (0.0361 m^2) by the DSC module percentage area per glass block and it coincides with the dimensions of the detector, so it is implicitly considered in the calculation.

The optical model presented in this work is based on a set of conservative assumptions and is intended to qualitative identify the most efficient of DSC-integrated glass blocks among the different configuration studied.

Results are summarized in Table 5.19, where main parameters involved in the calculation are indicated. In particular, it should be noted that the power read by the detector is the parameter that makes the difference among the configurations. De facto, it does not depend on module characteristics but only on the glass block configuration and, thus, on DSC position inside the product. Hence, changing the module should not affect the power stiking its surface, whereas it might change the efficiency and, thus, the output power.

Configuration		1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2
Light source dimension	(m)	0.190	0.192	0.190	0.192	0.190	0.192	0.190	0.192
Glass Block dimension	(m)								
Detector dimension	(m)	0.170		0.184		0.144		0.154	
DSC module dimension	(m)								
DSC module area percentage	(m)	80.06%	78.40%	93.78%	91,84%	57.44%	56.25%	65.70%	64.33%
Power of the light source	(W)	36.10	36.86	36.10	36.86	36.10	36.86	36.10	36.86
Power read by the detector	(W)	28.90	28.90	33.86	33.86	16.59	16.59	10.74	11.28
Power of the Glass Block [efficiency = 5%]	**(W)**	**1.44**	**1.44**	**1.69**	**1.69**	**0.83**	**0.83**	**0.54**	**0.54**

Table 5.19 - Table summarizing the main parameters involved in the simulation for the calculation of the power of each glass block configuration

5.7.2.3. Objective 3: Absorption of the layers constituting the glass blocks and g-value

The procedure for the assessment of the g-value of glazing is detailedly indicated in the standard EN 410:2011 and, as it has already been underlined, it requires the solar direct transmittance T_{sol} and the solar absorptance A_{sol} of each of the layers constituting the glass block: how to obtain the first has already been explained in paragraph 5.7.2.1, whereas the second has to be calculated for the evaluation of the secondary heat transfer factor.

For the evaluation of the solar absorptance of each of the layers constituting the glass block in the four configurations, two simulations are run, as described in Table 5.18, by positioning the detector right in front and beyond each layer. The difference between the two power values recorded by the detector provides the energy absorbed by each layer. The process is repeated as many times as the number of layers involved.

The Configurations 1, 2 and 3 are considered as double glazing, whilst Hypothesis 4 as a triple glazing. The conductance values that are required for the calculation have been provided by Comsol analyses on DSC-integrated glass blocks, considering an outside temperature of 32°C and and inside temperature of 20°C. The internal and external heat transfer coefficients were set at the values corresponding to “conventional” soda lime glass conditions and, in particular, at 8 W/m^{2}K and 23 W/m^{2}K, respectively.

Results are reported in Table 5.20 in the next paragraph, where they are widely discussed and compared among each other.

5.7.3. Discussion of the Results

The results of the analyses on the four DSC-integrated glass blocks, in the two sets of configurations (with and without profiles in plastic material), are shown in Table 5.20, where the DSC module area percentage per glass block (not to be confused with the active area percentage, AA%) is indicated for each configuration.

The following simulation outputs are reported: transmittance in the solar spectrum (solar transmittance, T_{sol}) and in the visible spectrum (visible transmittance, Tvis), solar factor (g value), and peak electrical power per glass block (P) expressed in Watt (Wp).

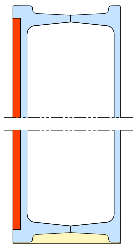
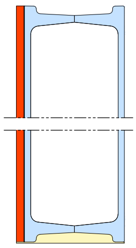
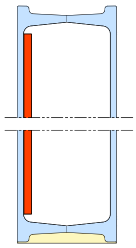
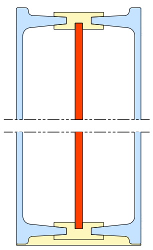
		AA%	Tsol (%)	Tvis (%)	g (%)	P (W)
		-	36.7%	12.3%	53.00%	-
	1.1	80.06%	17,06%	9.49%	36,05%	1.44
	1.2	78.40%	15,93%	8.79%	34,72%	1.44
	2.1	93.78%	16,22%	7.78%	35,91%	1.69
	2.2	91.84%	14,69%	7.12%	34,98%	1.69
	3.1	57.44%	19,85%	14.81%	36,94%	0.83
	3.2	56.25%	17,90%	12.39%	34,92%	0.83
	4.1	65.70%	12,80%	5.57%	37,22%	0.54
	4.2	64.33%	11,28%	5.17%	40,29%	0.54

Table 5.20 - Summary of the results from Zemax

As it is possible to see in Table 5.20, the optical performance of the glass block in the different configurations depend mainly on the spectral characteristics of the DSC module used. Indeed, being the module used the same, the difference among them never overcomes 10 percentage points: solar transmittance ranges from 11.28 to 17.90%, in the first set of configurations (1.1, 2.1, 3.1, 4.1) and 12.80 to 19.85%, in the second set of configurations (1.2, 2.2, 3.2, 4.2). Visible transmittance, instead, ranges from 5.57 to 14.81%, in the first set of configurations and 5.17 to 12.39%, in the second set of configurations.

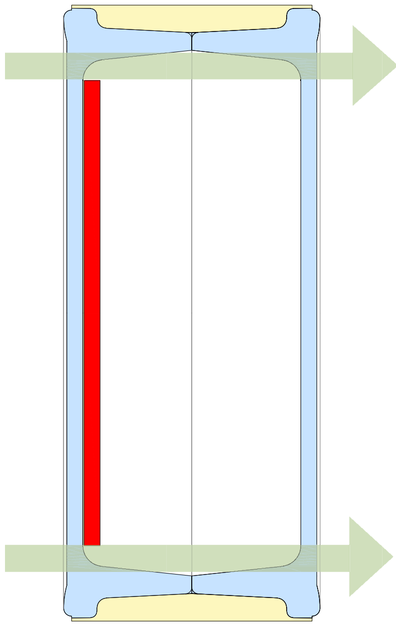


Figure 5.14 - Drawing illustrating the high-transparency portion in Configuration 3

Configuration 3 displays the highest visible transmittance: this is due to the lowest module area percentage of this configuration, translating into the fact that highly transparent glass occupies the largest area per glass block among the four hypotheses. In particular, differently than in the other configurations, in Configuration 3 the visible transmittance of the whole product results higher than that of the DSC module alone (12.33%), even if it is coupled with other layers. This is probably due to presence of a highly transparent portion, highlighted by the green arrows in Figure 5.14, around module perimeter corresponding to the part where glass shell internal surface is curved and linked with lateral sides of the glass block. The increase in visible transmittance is not relevant enough to represent a significant advantage in terms of optical performance of the product. On the other hand, the lowest module area represents a negative aspect for the electricity production; however, Configuration 3 is not characterized by the lowest power. Configuration 4, in particular, despite not having the lowest module area percentage has the lowest calculated power output (0.53 Wp), basically due to the position of the module inside the glass block, with the glass shell and an air layer in front of it.

On the other hand, despite not having the highest module area percentage, Configuration 4 is also the least transparent not only because it is the only configuration that presents three different “glazing” layers, but especially due to the presence of the thermal belt in plastic material, which is opaque to light. For this reason, in configurations 1.2, 2.2, 3.2 and 4.2, the presence of plastic, used for the profiles constituting the support structure of the panel and for the thermal belt, determines a decrease in the optical performance compared to the first set of configurations, analysing “unframed” glass blocks.

The analysis of the results shows also that there are not significant differences among the four configurations either as regards the solar factor (g-value). The highest g-value corresponds to the Configuration 4, despite the smallest solar transmittance, confirming the results obtained in WINDOW only regarding the so-called “vision area” of the device. This is mainly due to the solar heat absorbed by the DSC module, which is not in contact with the external environment and, therefore, is not able to fully exhaust the heat accumulated.

Since, as already underlined, the solar and optical performance parameters do not change significantly among the different configurations, Configuration 2 can be considered the best options based on the estimated electrical output: indeed, the latter is equal to 1.69 Wp and it is the highest among the four, since here the module is placed on the external side of the product, closest to sun rays, and it is characterized by the largest module area percentage. However, as already underlined, technological reasons (e.g. related to product resistance to atmospheric agents and degradation) may justify preferring, despite of the smallest active area and, thus, the smaller power output, one of the folllowing: Configuration 1, where a glazed border, despite subtracting some active area might help ensure higher mechanical tightness to the whole subcomponent; Configuration 3, where the DSC module is on the internal face of the glass shell and therefore “protected” from the external environment. In this sense, further studies on prototypes, currently in progress, are fundamental for choosing the best solution.

After having discussed Zemax results, it could be of relevance to compare them with those obtained from WINDOW. With Zemax it has been possible to take into account the whole three-dimensional model of the product, including glazed border and plastic supporting structure (that is opaque to light), obtaining more detailed information for the characterization of the DSC-integrated glass block performance. From the graph in Figure 5.15, it is possible to see that in Zemax there is not a significant change in the overall performance between “framed” and “unframed” configurations. The same graph shows, instead, that there is a notable difference with the results on the “unframed” configurations, obtained in WINDOW, which only referred to the vision area of the product (i.e. the part where the glass block section is characterized by a mere sequence of parallel glazed surfaces, accounting for approximately 70% of the area of the product in the 190x190mm glass block). This difference becomes less important, if we consider the “framed” product configurations[49], demonstrating the validity of WINDOW software for a preliminary study and for the approximation of product performance, besides the assessment of glass block vision area behaviour. In particular, as regards visible transmittance calculations, the above difference results practically negligible in all cases, unless of Configuration 3: here, in particular, the already discussed increase in visible transmittance (Figure 5.14) might be accounted for, when needed, by considering an additional reduction of DSC device active area, either *ex-ante* in the procedure described in paragraph 5.6.6 or *ex-post* by applying an appropriate correction factor to the results.

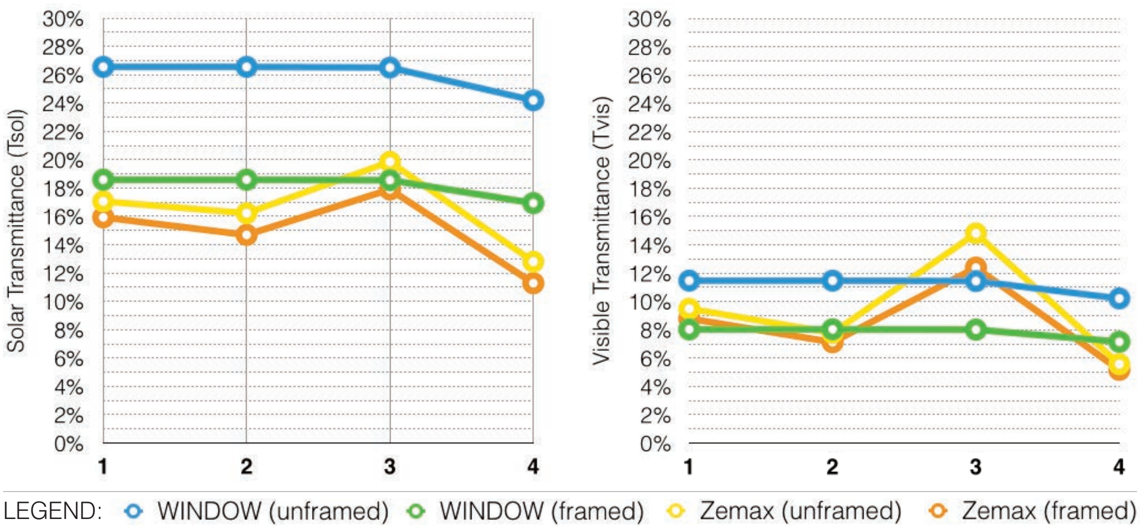


Figure 5.15 - Graphs comparing WINDOW and Zemax results in terms of both solar and visible transmittance

5.8. Summary Considerations

The analyses reported in the previous paragraphs allowed for a detailed analysis of the optical, thermal and energy performance of the DSC-integrated glass block, according to the main possible positions of the DSC module inside the product: on the outer surface (Configurations 1 and 2), on the inner surface (Configuration 3) of the sun exposed glass shell and inside the cavity (Configuration 4). All results are summarized in Table 5.21.

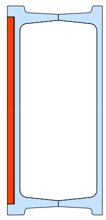
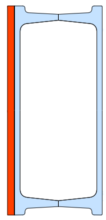
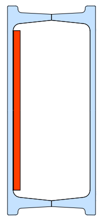
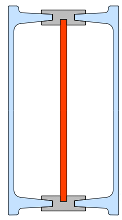
		WENGER'S DSC-INTEGRATED GLASS BLOCK (air-filled configurations)			
		Configuration 1	Configuration 2	Configuration 3	Configuration 4
					
Dimensional features					
Thickness (mm)		86	86	80	100
Module dimension (mm)		170	184	144	154
Module area percentage		80.06%	93.78%	57.44%	65.70%
Thermal performance					
U_{2D} (W/m²K)	Unframed	2.9	2.9	3.0	2.0
	Framed	2.9	2.9	3.0	2.0
U_{3D} (W/m²K)	Unframed	2.9	2.9	3.0	1.7
	Framed	2.9	2.9	3.0	1.8
Light and Solar properties					
T_{vis}	Vision Area	11.47%	11.47%	11.44%	10.21%
	Whole GB framed	8.79%	7.12%	12.39%	5.17%
T_{sol}	Vision Area	26.55%	26.55%	26.50%	24.19%
	Whole GB framed	15.93%	14.69%	17.90%	11.28%
g-value	Vision Area	35.10%	35.10%	35.30%	45.00%
	Whole GB framed	34.72%	34.98%	34.92%	40.29%
Electrical performance (η=5%)					
Percentage of solar radiation reaching module surface		100%	100%	89%	70%
Power Peak (Wp)		1.44	1.69	0.83	0.54
Area needed for 1kWp (m²)		25.5	21.8	44.4	65.3
Temperature distribution					
DSC surface temp. (°C)		51.3	51.3	52.3	67.2
GB inner surface temp. (°C)		37.4	37.4	37.8	44.3

Table 5.21 - Summary of main results of the multi-software energy performance analysis on DSC-integrated glass block according to the four patented configurations, defined in Corrao et al. (2013)

Configurations 1 and 2 are the most promising as for the electrical performance, due to wider module area, direct exposure of the DSC to the sun and limited warming-up of the module: fixing the conversion efficiency to 5%, the power peak of the glass block is equal to 1.44 and 1.69 Wp, respectively, resulting into a power density of 39 W/m^2 and 46 W/m^2.

The optical performance of the so-called vision area in Configrations 1 and 2 are very close among each other, since this parameter depends mainly on the characteristics of the DSC module more than on its position. Such differences increase when considering the transmittance of the whole product, accounted for by means of Zemax software, including in the optical study also glazed border and profiles. In particular, in this study, Configuration 3 has been assessed as the one providing the highest optical transmittance, whereas also the lowest module area percentage. This aspect, related to the particular shape of the glass shell, represents a downside for the electricity production as also does the presence of the glass shell in front of the module reducing, even if quite limitedly, the amount of energy striking its surface. On the other hand, the fact that the module is located inside the product may be a relevant advantage for reasons related to the easier electrical connection of the glass block and also because of the protection the the glass shell might provide to the PV device. Temperatures in Configuration 3 are higher than in the configurations where the module is placed on the outer face of the glass block (1 and 2), even if not significantly different: the absence of ventilation on the module, however, may represent a limit as regards the electrical production. The good temperature performance of the DSC technology has, however, already underlined.

Configuration 4 seems the least promising due to notable overheating phenomenon inside the glass block due to high energy absorption, lower amount of sunlight striking on module surface (an aspect that leads to lowest electrical power), smallest visible and solar transmission values. The overheating is due to the position in the middle of glass block cavity of the module, which thus results not ventilated and insulated from the external environment. This can generate a notable drop in product electrical and thermal performance as well as expose it to thermal stresses. The drop in product electricity conversion become even more significant if we also consider the possibility of self-shading on the solar device, when sun is not striking perpendicularly on the surface of the product in real installation conditions. The position of the module inside the glass block as well as the presence of the thermal belt have the advantage to provide Configuration 4 with the best thermal transmittance, but all other issues related to the DSC module performance lead to have it excluded.

To sum up, the integration of the solar module, due to its optical and solar characteristics, produces, in general, a notable decrease in visible light transmission of the glass block, a smaller but still relevant decrease in solar transmittance and, consequently, also on the total solar energy transmittance of the product. This latter aspect could be useful especially for the improvement of summer performance of the building envelope made of such glass blocks and becomes an advantage of great relevance, compared to other glazing systems characterized by high values of solar gain, especially in cooling-dominated contexts (such as, for example, the Mediterranean Basin); on the other hand, the performance related to daylighting and solar gain need to be carefully thought especially in cold climates.

In this regard, it must be also underlined that significantly more transparent DSC modules can be obtained treating the properties of the constituent layers; in some cases cell transparency even reaches approximately 50%, with a corresponding but not proportional decrease in conversion efficiency. More analyses with modules that are characterized by different optical and energy performance, have been carried out and are presented later in this chapter.

Focusing on thermal transmittance (U value), the four hypotheses, as they have been simulated until now, are not sufficiently thermally insulating. As already highlighted, indeed, DSC module influence on the U value of the final product is limited and therefore other operations should be foreseen in order to improve product thermal transmittance, based on the considerations made in paragraph 5.5. Here, in particular, the analyses completed on thermally optimized glass block configurations demonstrated the possibility of increasing the energy performance of the product up to very efficient U values. Integrating such better insulating configurations with DSC modules can allow for the attainment of efficient thermal transmittance values, while also adding the plus-value of energy production.

In these cases, the main challenges are how to maintain efficient solar factors and appropriate light transmission values according to building requirements, acceptable temperatures on both DSC module and glass block surfaces, and maximum PV production levels.

5.9. WINDOW analyses taking into account different DSC modules

Further analyses have been executed by means of WINDOW software by considering other "types" of DSC modules, characterized by different optical and electrical properties as well as colors, in order to evaluate the potential relapses related to their use for the integration with the glass block according the four main configurations formulated. In particular, two DSC modules, manufactured by the Swiss company glass2energy (g2e), in two different colors (red and green) were analyzed, starting from experimental measurements performed on samples through the use of an UV/Vis/NIR spectrophotometer equipped with an integrating sphere and provided by the manufacturer itself.

5.9.1. Device Characterization

The same procedure, described in paragraph 5.6.3 for the inputting of data in Optics software and aimed at the full characterization of the device, was adopted. Other information related to conductivity and surface emissivity were inserted as well, by making the same assumptions as in the previous analyses regarding Wenger's DSC module. In this case, a 6.5-mm-thick module was analyzed although lower thickness of the glazed layers constituting the DSC sandwich could be used[50] for the integration with glass block without any significant changes expected in the optical behavior of the device. The data that were provided by the manufacturer are referred to the active area only and subsequently they were weighed according to the actual active area percentage (75%, accounted as described in paragraph 5.6.6), in order to obtain the global properties of the device. Table 5.22 summarizes global optical and solar properties (obtained through Optics, starting from measured detailed spectral data) of the two analysed modules and relates them with those regarding Wenger's DSC already widely discussed.The table allows for some comparisons among the three different modules as well as for some considerations on the effects of highly transparent non-active spaces inside the devices on DSC module optical and color rendering performance. Results indeed regard the global optical properties of both the 100%-active and 75%-active module.

Red modules show a quite similar behaviour as for the optical performance. This is due to the fact that they absorb or transmit light according to similar wavelength spectra, due to the colour of the dye used (that, of course, influences the perceived color of the device). Wenger's DSC seems to be slightly more transparent in the near and far infrared ranges (although the behaviour in these ranges had to be assumed, according to what indicated in par. 5.6.1.1, since it was not provided in literature). Indeed, despite the lower visible transmittance, the device has a 2-point higher transmittance in the solar spectrum than the other red device (35.7% and 33.4% respectively). As for the optical performance, green DSC module provides the highest visible transmittance (close to 22%) as well as the lowest solar transmittance. This means that it will be absorbing more than the other two DSC devices outside visible range.

As for the electrical performance, in particular, the efficiency declared by g2e is around 4%, translating into approximately 35 Wp per square meter power density. In this sense, it should be noted that Wenger's DSC, which is a small lab scale device and therefore is characterized by an optimized conversion efficiency (7.6%[51]) is more performing than the two g2e devices (whose efficiency is calulated on a 6000 cm^2 module, 600x1000x6.5 mm).

	Wenger's DSC		g2e Red		g2e Green	
	100%-active	75%-active	100%-active	75%-active	100%-active	75%-active
Thickness (mm)	6.125	6.125	6.500	6.500	6.500	6.500
Solar Transmittance	0.357	0.420	0.334	0.403	0.308	0.384
Solar Reflectance, front	0.100	0.112	0.093	0.091	0.091	0.092
Solar Reflectance, back	0.100	0.112	0.093	0.091	0.091	0.092
Visible Transmittance	0.128	0.294	0.125	0.292	0.217	0.361
Visible Reflectance, front	0.084	0.085	0.083	0.085	0.084	0.091
Visible Reflectance, back	0.084	0.085	0.083	0.085	0.084	0.091
Colour Transmittance (CIE L*, a*, b*)						
Colour Rendering Index	0.98	59.53	0.63	55.59	80.31	91.83

Table 5.22 - Summary Table of the main properties of the three modules used for the optical analyses

However, the scale-up of the cell up to the dimensions of a module suitable for the integration with glass block (from about 16x16 cm^2 to 30x30 cm^2) would determine a decrease in Wenger's PV performance from lab scale that is difficult to quantify or predict; in parallel, it is expectable an increase in g2e efficiency passing from their large dimensions to the smaller dimensions that are suitable for the integration with glass block.

5.9.2. Discourse on the Colour Performance of the devices

Besides the aspects concerning the appearance of the glass block, the colour difference of the three devices result in significantly different colour rendering performance, as it is possible to see in the last row of Table 5.22. Looking at the Colour Rendering Index (CRI) values derived from the analysis of the spectral behavior of the DSC devices by means of Optics, we can highlight some important aspects. In particular, it is also possible to make some interesting considerations on the applicability of these devices, according to the regulatory indication provided in the standard UNI EN 12464-1:2011 regarding lighting of indoor work places.

First of all, there is a big difference among the CRI related to the two red devices and the green one. Indeed, the first two are characterized by very low CRI, close to 0, in the 100%-active module, which are quite opaque to visible light and red-colored. This would limit the applicability of the two red DSC modules as semitransparent elements of glazed façades/roofs, despite all other related benefits. Contrarily, the green module is characterized by a notably higher visible transmittance and by a different color that translate into a significantly higher CRI, slightly above 80 in its active part.

However, all modules present non-active and highly transparent spaces between one cell and the other; such spaces are also characterized by very good CRI, close to 90. Having weighed the properties of active and non-active spaces according to an average active area percentage of 75% and 25% respectively, different results have been obtained not only in terms of visible and solar transmittance, but also in terms of CRI. In 75% active area red modules CRI grows up to 55.6 and 59.5, close to 60. This is still not sufficient for several building spaces and activities, but it is enough for circulation areas and other rooms.

Considering a lower than 75% active area percentage could be a way to increase CRI and allow for the studied red modules to be used for other types of spaces; however, this would generate a decrease in the active area and thus in the electricity performance of the DSC-integrated glass block. Otherwise, for example, coupling highly transparent surfaces (such as non-PV glass blocks or clear glass systems) with DSC-integrated glass blocks could produce an overall increase of the CRI related to the light transmitted across the building envelope. Even in this case, this implies a lower available surface for PV. Different red tones for DSC module could have an influence on this aspect too (even if only a minor change has been registered between the two analyzed types of red modules) and diverse transparency values (related to the thickness of the layers and to the nano-structure of the DSC device) could have an an impact on CRI too.

The green module, instead, has already a very good color rendering performance but, considering an active area of 75%, a clear and highly transparent non-PV area of 25% and weighing the respective spectral properties accordingly, CRI reaches very good overall 91.8 value, which would allow using it in any of the situations indicated in the sandard UNI EN 12464-1:2011.

5.9.3. Discussion of the Results on the four PV-integrated Configurations

The above described procedure for the preliminary optical, thermal and electrical characterization of the DSC devices for integration with glass block, could be repeated with any type of module and allows for a preliminary comparison among the DSC solutions at disposal. After having characterized the DSC device and input all the required characteristics, the analyses on the four patented configurations of DSC-integrated glass blocks can be performed. The four configurations have all been analyzed by taking into consideration the three above-described modules, in order to evaluate the best performing ones after the integration with the glass block. The main performance parameters regarding the four patented glass block configurations, integrated with each of the two new modules analysed (g2e red and green), are reported in Table 5.23. Here, the results already discussed regarding the integration into the glass block of the Wenger's DSC module are inserted as well, in order to allow for a more direct comparison of all the solutions.

	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
Module area %	81%		94%		58%		66%	
Thickness (mm)	86.5		86.5		80		100	
U_{2D} (W/m²K)	2.4	2.9	2.4	2.9	2.5	3.0	1.7	1.9
U_{3D} (W/m²K)	2.6	2.9	2.6	2.9	2.7	3.0	1.6	1.7
g2e green (100%)								
SHGC	34.30%	36.70%	34.30 %	36.70 %	34.80%	37.00%	47.70%	47.40%
T_{vis}	20.04%		20.04%		19.97%		17.73%	
T_{sol}	22.30%		22.30%		22.29%		20.85%	
Power (η=4%)	1.16 W		1.35 W		0.66 W		0.45W	
g2e red (100%)								
SHGC	35.70%	37.60%	35.70%	37.60%	36.20%	38.20%	48.50%	48.20%
T_{vis}	11.12%		11.12%		11.09%		9.91%	
T_{sol}	23.85%		23.85%		23.83%		22.45%	
Power (η=4%)	1.16 W		1.35 W		0.66 W		0.45 W	
Wenger (100%)								
SHGC	37.00%	38.60%	37.00%	38.60%	37.40%	39.00%	46.70%	46.50%
T_{vis}	11.47%		11.47%		11.44%		10.21%	
T_{sol}	26.55%		26.55%		26.50%		24.19%	
Power (η=5%)	1.44 W		1.69 W		0.83 W		0.54 W	

Table 5.23 - Main performance parameters regarding the four patented glass block configurations integrated with both g2e's green and red modules as well as Wenger's (100%-active area)

The same considerations made in the previous analyses regarding Wenger's DSC module can be made here as well. First of all, it should be underlined that the variation of the solar module integrated into the glass block does not have any relapses on product U value, considering both vision area (WINDOW) and the whole glass block product (Comsol Multiphysics); all modules, indeed, have the same assumed conductivity and behave as "simple" glazed sheets glued to one of the glass shells or inserted into the cavity of the product. In this second case (Configuration 4), it is the position of the module in the centre of the cavity that generates a sharp reduction in product U value. The change of some millimeters in the thickness of the solar device does not generate any variation in the U value of the product. Thus the U value of the product only changes due to the variation of the glass block configuration and not of the modules.

The variation of the solar module used is, instead, of great relevance when analyzing the other optical and thermal properties, examined when the sub-component is irradiated. As regards the red devices, which have quite close optical and solar properties, there are not significant changes from one module to the other, whereas the green module is characterized by a significantly different performance, especially as regards solar and visible transmittance. The visible transmittance of the glass block integrated with the green module ranges from 17.73% to 20.04%, which is slightly higher than the values registered in the red modules, whose light transmission performance does not overcome 11.47%. Depending on the requirements of transparency of the building envelope, this difference might have a significant weigh in the choice of the green instead the red modules.

On the other hand, the solar transmittance T_{sol} of the glass block is lower when the product is integrated with the green module and this also reflects into a lower solar heat gain coefficient (SHGC); however, the differences are not significant to justify preferring one configuration against the other, based only on these two solar properties.

In this sense, it is possible to say that the green DSC-integrated products are characterised by a higher Light-to-solar-gain ratio (LSG) that indeed is (as defined in equation [6], paragraph 5.4.3) the ratio of the visible transmittance, higher in the green module, to the solar heat gain coefficient, only slightly higher in the red modules but yet quite close among the different solar devices analyzed. This corresponds to a more efficient daylighting performance of the glass block integrated with the green module, being the solar heat gain performance very similar.

For the sake of completeness, analyses have also taken into account the three DSC modules with 75% active surface (and the remaining 25% made of highly transparent, colorless and inactive spaces). In the case of g2e modules, this also corresponds to the actual "form" of the modules, so this additional analysis has been also necessary for making the analyses as accurate as possible. Results are reported in Table 5.24.

The green-g2e-integrated glass blocks reach a maximum visible transmittance value of 33.03%, whereas the use of the red g2e allows reaching a maximum value of 26.36% (in the same configurations). Also the solar transmittance and solar heat gain coefficient in-

	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
Module area %	81%		94%		58%		66%	
Thickness (mm)	86.5		86.5		80		100	
U_{2D} (W/m^2K)	2.4	2.9	2.4	2.9	2.5	3.0	1.7	1.9
U_{3D} (W/m^2K)	2.6	2.9	2.6	2.9	2.7	3.0	1.6	1.7
g2e green (75%)								
g-value	39.90%	41.70%	39.90%	41.70%	40,40%	42,30%	50,80%	50,60%
T_{vis}	33.03%		33.03 %		32.95%		29.48%	
T_{sol}	28.91%		28.91 %		28.86%		26.83%	
Power (η=3%)	0.87 W		1.02 W		0.55 W		0.34 W	
g2e red (75%)								
g-value	41.00%	39.90%	41.00%	39.90%	41.50%	43.20%	51.50%	51.30%
T_{vis}	26.36%		26.36%		26.30%		23.58%	
T_{sol}	30.03%		30.03%		29.99%		28.02%	
Power (η=3%)	1.16 W		1.35 W		0.66 W		0.45 W	
Wenger (75%)								
g-value	42.80%	44.40%	42.80%	44.40%	43.20%	44.90%	52.10%	51.90%
T_{vis}	26.61%		26.61 %		26.55%		23.80%	
T_{sol}	32.08%		32.08%		32.03%		29.34%	
Power (η=3.75%)	1.08 W		1.27 W		0.62 W		0.42 W	

Table 5.24 - Main performance parameters regarding the four patented glass block configurations integrated with both g2e's green and red modules as well as Wenger's (100%-active area)

crease in the 75%-active configurations, even if in a minor measure, especially as regards the latter where the higher solar transmittance also translate into a lower heat transfer coefficient towards the inside.

All in all, changing the optical characteristics of the modules used for the integration become a significant aspect for the definition of the performance of the product. Understanding the main relapses of the integration with the glass block of a specific DSC module, in order to define its main performance parameters (i.e. T_{vis} and SHGC), is therefore very important to evaluate the applicability of this building product into architectural projects. At the same time, the thermal transmittance, depending on the other subcomponents of the specific glass block configuration more than on the module type, must be considered carefully. This would be the object of the following paragraph, where some new configurations of the DSC-integrated glass blocks, also optimized as regards the thermal insulation performance, are studied and discussed.

For more detailed reading and for a more in-depth comparison of the results regarding both 100%-active and 75%-active g2e modules, in the two colors analysed (green and red), Tables 5.A2 and 5.A3 are reported in the Appendix to this chapter. These contain all relevant parameters deriving from the analyses.

5.10. Analyses on New DSC-integrated Configurations

Due to the insufficient (or, at least, not sufficient in any climate contexts) thermal insulation performance of the four analysed DSC-integrated glass block configurations, a series of new configurations have been defined starting from the considerations made in the previous paragraphs. In order to improve the thermal transmittance of the product, one or more of the following operations could be foreseen:

- insertion, inside of the cavity, of one or more sheets of glass (clear or low-emissive);
- use of the thermal belt;
- evacuation of the cavity;
- filling of the cavity with argon (and/or other appropriate gases).

The objective is the improvement of glass block U value, without reducing significantly visible light transmission performance of the DSC-integrated glass block.

The insertion of the thermal belt, as already underlined from the simulations in Zemax, does not have a relevant effect on global optical performance of the "framed" product and has no effect on the performance vision area of the product. The thermal belt would be a good solution to further reduce the U value of the product (due to 20-mm break between the outer and inner glass shells), but it has already been highlighted in paragraph 5.5.4 that its use alone is not sufficient for the attainment of acceptable U values. Therefore, it is coupled with other subcomponents (i.e. glass, low-e glass).

The insertion of a glazed sheet inside the cavity of the product has already been individuated as a possible solution for the improvement of the U value of the product, but for further decrease of the thermal transmittance the use of a low emissive glazed sheet could be pursued. For this scope, among the very wide choice of commercial products belonging to the IGDB, the low-emissive "ClimaGuard Premium on Float ExtraClear Glass" manufactured by Guardian Europe and characterized by extra clear appearance was selected for the analyses. Main properties of this glazing are reported in Table 5.25. It is important to note that, in this glass product, a very high visible transmittance is maintained so that the light transparency — which is of great relevance to compensate to low visible transmittance of the DSC devices — is guaranteed; the emissivity of one of the two surfaces of the glass is very low (0.038) and this helps reduce winter thermal losses (lower U value) and summer heat gains as well; solar transmittance is clearly lower than that of a clear glass, due to in-

	ClimaGuard Premium
Thickness (mm)	4.000
Thermal Conductivity (W/mK)	1.000
Solar Transmittance	0.575
Solar Reflectance, front	0.327
Solar Reflectance, back	0.277
Visible Transmittance	0.879
Visible Reflectance, front	0.047
Visible Reflectance, back	0.059
Infrared Transmittance, Tir	0.000
Emissivity, front	0.038
Emissivity, back	0.840

Table 5.25 - Physical, Optical and Thermal Properties of "ClimaGuard Premium on Float ExtraClear Glass"

creased solar reflectance, but yet it remains close to 60%. The objective of not reducing the visible transmittance significantly is thus achieved with the insertion of this glass product, however, different requirement as regards the optical transmittance of the glass block might lead to the use of other types of glazing, depending on the needs of each project and installation.

Analyses with Comsol and WINDOW have been executed (by considering both air-filled and evacuated cavity/ies) in order to identify main parameters related to product optical and thermal performance, whereas the considerations made on the electrical power are not expected to change from what assessed in Zemax. Only Configurations 1 and 3 will be taken into account, since: Configuration 4 has been excluded, in a first phase, for the issues described in paragraph 5.8; Configurations 1 and 2 can be considered equivalent for the purpose of these analyses, since they only differ because of the module area percentage, which can be taken into account in a second phase for calculations related to the electricity production.

For standardization purposes, Configuration 1 has been "modified" in order to guarantee an 80-mm thickness to the final product. Such modification has been made according to the considerations illustrated in paragraph 5.5.6.

The analysed configurations are illustrated in Table 5.26 and are all characterized by the use of the Thermal Belt, that allows for the interruption of the thermal bridge between the glass shells composing the glass block as well as for the insertion of one or more sheets of clear and/or low-emissive glass.

The simulations have been executed by taking into consideration Wenger's and Green g2e modules in both 100% and 75%-active configurations, in order to obtain a wider spectrum of results.

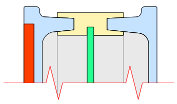
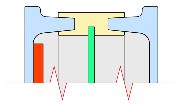
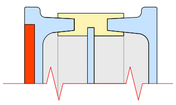
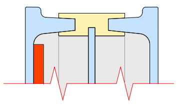
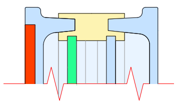
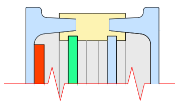
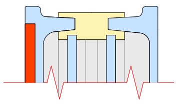
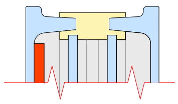
DSC outside (as in Configuration 1)	DSC intside (as in Configuration 3)	
1.01 	3.01 	Glass block with two cavities, Thermal Belt and one 4-mm sheet of low-emissive glass
1.02 	3.02 	Glass block with two cavities, Thermal Belt and one 4-mm sheet of clear glass
1.03 	3.03 	Glass block with three cavities, Thermal Belt, two 4-mm glass sheets, one of which low-emissive
1.04 	3.04 	Glass block with three cavities, Thermal Belt, and two 4-mm sheets of clear glass

Table 5.26 - New configurations of the DSC-integrated glass block, optimized as regards the thermal insulation performance

5.10.1. Discussion of the Results

In Tables 5.27 and 5.28 are reported the main parameters defining the energy performance (U value, solar heat gain coefficient, visible and solar transmittance, temperature on module surface) of the new DSC-integrated glass block configurations, just illustrated.

As regards the U value, the position of the DSC module outside (Table 5.27) and inside (Table 5.28) the glass block does not have any relevant effect on product U value; moreover, the standard thickness of the product is maintained in both DSC outside and DSC inside configurations. Therefore, the same configurations are characterized by identical results regardless of the position of the DSC module, either inside or outside the glass block: as expected, indeed, the U values, rounded to the decimal, coincide. Looking at the results, significant improvements can be highlighted, compared to the four patented configurations.

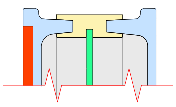
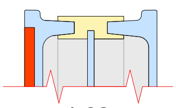
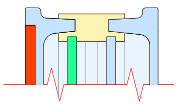
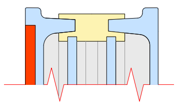
	DSC outside (as in Configuration 1)							
	 1.01		 1.02		 1.03		 1.04	
Cavity Filling	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
U_{2D} (W/m²K)	0.9	1.2	1.7	1.9	1.1	1.4	1.5	1.7
U_{3D} (W/m²K)	1.4	1.6	1.8	2.0	1.5	1.7	1.7	1.8
g2e green (100%)								
SHGC	19.10%	22,60%	28.50%	30.00%	18.20%	20.20%	24.80%	26.10%
T_{vis}	17.87%		18.29%		16.34%		16.76%	
T_{sol}	14.17%		19.05%		12.38%		16.34%	
DSC surface temp.	60.1	58.1	56.4	55.5	60.0	59.1	58.0	57.3
g2e green (75%)								
SHGC	25.10%	27.90%	34.00%	35.50%	23.80%	25.20%	30.10%	31.20%
T_{vis}	29.44%		30.14%		26.94%		27.62%	
T_{sol}	19.43%		24.96%		17.15%		21.68%	
DSC surface temp.	57.5	55.8	54.0	53.2	57.8	56.8	55.7	55.1
Wenger (100%)								
SHGC	21.00%	23.50%	31.50%	32.60%	20.10%	21.10%	27.70%	28.70%
T_{vis}	10.03%		10.36%		9.08%		9.39%	
T_{sol}	15.31%		22.50%		13.25%		19.16%	
DSC surface temp.	55.5	53.9	52.1	51.4	55.8	54.9	53.7	53.1
Wenger (100%)								
SHGC	26.60%	29.00%	36.80%	38.30%	25.30%	26.20%	32.70%	33.60%
T_{vis}	23.57%		24.19%		21.49%		22.10%	
T_{sol}	20.29%		27.56%		17.81%		23.80%	
DSC surface temp.	56.0	54.5	52.6	51.9	56.4	55.6	54.3	53.7

Table 5.27 - Main performance parameters regarding the thermally optimized glass block configurations, integrated with g2e's green and Wenger's modules (in both 75%- and 100%-active area), placed on the outside surface of the glass block (Configurations 1.01-1.04)

The minimum value of thermal transmittance is 1.4 W/m²K (Configuration 1.01 and 3.01) in 3D environment. In this case, the thermal transmittance is almost halved compared to the "basic" PV-integrated configuration (Configuration 1 and 3) analysed previously. Taking into account the 2D simulative environment, the obtained U value in the same configuration (1.01 or 3.01) is even more efficient (0.9 W/m²K, i.e. three times lower compared to Configuration 1 and 3). In this phase, 3D models are expected to be more reliable than 2D ones; however, experimental studies are currently ongoing in order to confirm this statement and to validate the results obtained.

The use of a low-emission glass sheet is the most effective of the operations for thermal transmittance optimization. In particular, it should be noted that it is more effective in two-cavity (1.01, 3.01) than in three-cavity configurations (1.03, 3.03).

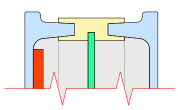
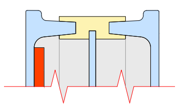
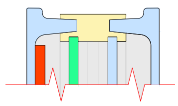
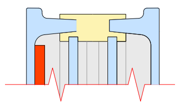
	DSC inside (as in Configuration 3)							
	 3.01		 3.02		 3.03		 3.04	
Cavity Filling	Vacuum	Air	Vacuum	Air	Vacuum	Air	Vacuum	Air
U_{2D} (W/m²K)	0.9	1.2	1.7	1.9	1.1	1.4	1.5	1.7
U_{3D} (W/m²K)	1.4	1.6	1.8	2.0	1.5	1.7	1.7	1.8
g2e green (100%)								
SHGC	19.10%	22.90%	28.80%	30.50%	18.20%	20.20%	25.10%	30.00%
T_{vis}	17.79%		18.18%		16.24%		16.62%	
T_{sol}	14.11%		18.99%		12.32%		16.27%	
DSC surface temp.	61.6	59.4	57.7	56.8	61.9	59.1	59.4	57.3
g2e green (75%)								
SHGC	25.00%	28.10%	34.30%	35.70%	23.80%	25.30%	30.30%	31.40%
T_{vis}	29.35%		30.01%		26.81%		27.46%	
T_{sol}	19.36%		24.88%		17.07%		21.59%	
DSC surface temp.	58.8	57.0	55.2	54.4	59.2	58.1	57.0	56.3
Wenger (100%)								
SHGC	20.90%	23.60%	31.70%	32.90%	20.00%	21.20%	27.80%	28.80%
T_{vis}	9.99%		10.31%		9.03%		9.33%	
T_{sol}	15.21%		22.43%		13.16%		19.07%	
DSC surface temp.	56.6	58.2	53.0	52.3	56.8	55.9	54.6	54.1
Wenger (100%)								
SHGC	26.50%	29.10%	37.00%	38.30%	25.20%	26.30%	32.80%	33.80%
T_{vis}	23.50%		24.09%		21.39%		21.97%	
T_{sol}	20.19%		27.47%		17.71%		23.70%	
DSC surface temp.	57.1	55.5	53.6	52.8	57.5	56.6	55.3	54.7

Table 5.28 - Main performance parameters regarding the thermally optimized glass block configurations, integrated with g2e's green and Wenger's modules (in both 75%- and 100%-active area), placed on the inside surface of the glass block (Configurations 3.01-3.04)

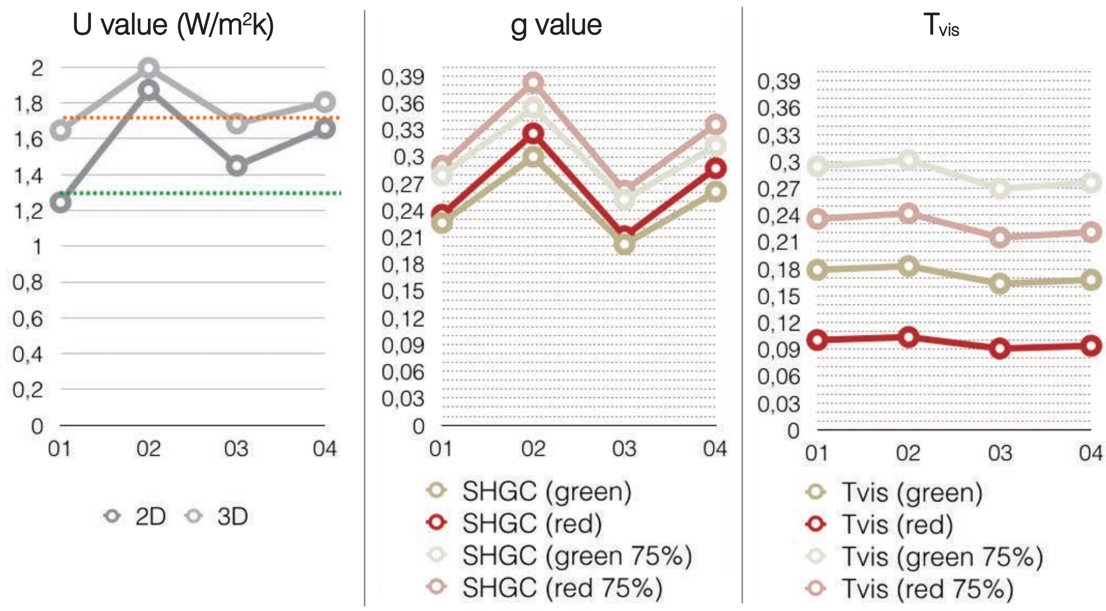


Figure 5.16 - Graphs summarizing main results regarding the new thermally-optimized and DSC-integrated glass block configurations. Both Wenger's and green g2e DSC module are considered

On the other hand, when a simple clear glass is considered, a quadruple glazing (1.04, 3.04) allows for a two-point reduction of the U value compared to triple glazing (1.02, 3.02).

The obtained U values are efficient if we compare them with those of commercially available glass blocks, but there are still some improvements needed to allow for the use of this product in all kinds of climate contexts and to bring the U value of the product below the green line in the left graph of Figure 5.16. Some of the possible strategies, directly involving the thermal belt material composition and design, have already been widely discussed in paragraph 5.5.8. Simulations have also considered the possibility to fill the cavity of the product with argon, which has lower thermal conductivity than air: on average, the U value decreased of 1-2 points in the argon-filled configurations.

Looking at the solar and optical results, the position of the DSC module outside or inside the cavity of the glass block does not generate any relevant changes in the performance of the product. Moreover, the increase of light transmission in Configuration 3 due to the lower active area (as explained in Figure 5.14, paragraph 5.7.3) is not taken into account due to the presence of the opaque thermal belt (needed for several reasons already mentioned previously in this work). Therefore, the choice of one position for the DSC module or the other can not be based on the results coming from the results reported in this paragraph. It should instead be subjected to different kinds of considerations, mainly related to the mechanical resistance and durability of the device.

Differently than its position, the optical and solar characteristics of the module are obviously very important for the definition of product's performance. The integration of the green module allows reaching visible transmittance (T_{vis}) values close to 30%, in 75%-active module configuration, whereas the maximum T_{vis} in the Wenger's red DSC hardly overcomes

24% (in 75%-active configuration). Being the module the same, the visible transmittance does not change significantly from one configuration to the others: for example, T_{vis} results for 75%-active green DSC integrated into the glass block, belong to a very small range comprised from 26.81% to 30.14%. This is mainly due to the fact that the sub-components chosen for the improvement of the thermal transmittance of the glass block, in all new thermally optimized configurations, are highly transparent in the visible range. Depending on the visual comfort requirements of each installation, different types of glazing elements can be selected for glass block cavity subdivision and, as a result, lower values of transparency can be obtained. More in general, besides the visual performance, the characteristics of this element have an important effect in terms of solar performance that should also be accounted for.

Speaking in detail of the solar properties of the analyzed configurations, g2e green module is characterized by a 5-point lower solar transmittance than Wenger's red DSC (see Table 5.22). As a result, the Solar Heat Gain Coefficient (SHGC) is lower; however, the difference from the corresponding Wenger's DSC-integrated glass block configurations never overcomes 3 percentage points (as it is possible to see from the close position of red and green lines in the middle graph of Figure 5.16). This is probably due to the fact that, despite the higher transparency in the visible range, the green module transmits a smaller portion of the solar energy spectrum and absorbs a bigger amount of solar energy, thus increasing the secondary heat transfer factor, defined as a part of the Solar Heat Gain Coefficient in equation [1]. De facto, also the temperature on module surface is higher in the green than in red module. Looking more in detail at the SHGC, the lowest values are obtained through the insertion of a low-emissive glass sheet inside the product, reflecting a substantial part of the solar energy, as it is possible to see from its optical properties in Table 5.25.

For more detailed information and for a more in-depth comparison of the results of WINDOW and Comsol analyses regarding Wenger's and green g2e modules (both in their 100%- and 75%-active), Tables 5A.4, 5A.5, 5A.6, 5A.7 are reported in the appendix to this chapter. These contain all the results obtained from the above analyses.

5.11. Conclusions and Future Developments

The here-analysed building product represents a multi-functional solution, useful for the construction of sustainable, translucent, colourful envelopes that could save energy, while self-generating it. Several other applications are possible thanks to the energy efficiency, constructional, and aesthetic features of the DSC-integrated glass block (e.g., urban equipment, spatial dividers outside the envelope or even within the envelope, in order to exploit DSC sensitivity to artificial light). In these cases, specific performance in terms of thermal insulation are not needed and the "basic" DSC-integrated glass block configurations, studied in deep in this chapter, could be already used. However, this chapter has also focused on assessing the energy performance of the product for its use as a glazed technical element of the building envelope, where the thermal transmittance of any glazed product represents a fundamental parameter for the choice of one solution rather than another.

Improving the U value of the product is also important to allow for the use of this product in diversified climate contexts, for example, in Northern countries, where U value limits are getting stricter and stricter, but it is not the only aspect to take into account. De facto, even more importantly if we consider Northern countries, characterized by cold climate and low values in terms of global solar radiation, it could be of great relevance to maintain high solar gains and appropriate light transmission values according to building requirements, acceptable temperatures on the surfaces of both the DSC module and the glass block, and maximum PV production levels. In this sense, the choice of the optical characteristics for the integrated DSC module is a fundamental part not only of the design of this innovative product but also of its best use as a technical element of the building envelope. Indeed, a great variety of results, in terms of energy production, thermal, optical and, last but not least, aesthetic performance, can be achieved using DSC modules with different combinations of transparency and colour as input for the simulations, as the analyses on two modules of different colours and optical performance have demonstrated[52].

The analyses showed the importance to consider carefully also the characteristics of the glazing elements to be introduced inside glass block cavity for its thermal transmittance optimization, since they might contribute to the attainment of specific performance levels and thus have an impact on the applicability of the product itself. This aspect, mixed with the versatility of DSC technology and with the modularity of the analysed product, makes it quite easy to obtain an even wider range of design possibilities for the building envelope, simply by assembling different glass blocks (in terms of shapes, colours, degree of transparency, dimensions, finishing, etc.) in potentially unlimited combinations. For example, if a higher level of natural light is required inside the building, PV-integrated glass blocks could be coupled with clear ‘non-PV’ ones which allows the obtaining of diversified results in terms of daylighting and also in terms of façade aesthetics, by using each glass block as a tile of a mosaic design.

Further analytical studies and laboratory tests will be carried out to further characterize the performance of this novel component for the building envelope, not only in terms of electrical, optical and thermal performance, but also as regards all essential building requirements defined in CPR 305/2011. Experimental testing, in particular, is of great relevance also to verify the validity of the numerical approach comparing the results of this study to the real behavior of prototypes. At this point, indeed, it is important to validate, through experimental testing on prototypes, the results obtained and, more in general, the methodology adopted here for the characterization of the DSC-integrated glass block. For example, as regards the g-value, which has been assessed analytically according to the standard calculations method suggested by the EN 410, experimental measurements could be the best way to verify and, eventually, to adjust the value of this performance indicator referred to the assembled component. As already introduced at the beginning of this chapter, one of the objectives is indeed to define an easily replicable and reliable methodology to quickly obtain the main characteristics of the DSC-integrated glass block components deriving from a change in the physical properties of the solar cells selected for the integration.

Notes

1) Cf. http://www.comsol.com.

2) WINDOW has the advantage to easily simulate different configurations, correlating the results in terms of both thermal and optical properties, allowing qualitative and quantitative considerations on advantages and disadvantages of the analyzed configurations.

3) Cf. SEVES Glass Block (2006) and SSV (2008).

4) All objects emit invisible thermal radiation (especially in the IR); the warmer they are, the more thermal radiation they emit. The ability of a material to absorb and emit radiant thermal energy is called Emissivity and depends on surface characteristics and internal composition. Glass is characterized by a high emissivity, typically equal 0.837, which means that about 84% of the IR energy it absorbs is emitted by the glass surfaces as heat through radiation.

5) The parameter “gradi giorno” (GG), literally "degree days", is a measure of how much (in degrees), and for how long (in days), outside air temperature was lower than a specific "base temperature" (or "balance point"). It is defined in EN ISO 15927-6/2007 and used for calculations relating to the energy consumption required to heat buildings.

6) Cf. SIA 380/1:2009. (2009). *L’energia termica negli edifici*. SIA Sezione Ticino, Bellinzona.

7) http://www.commercialwindows.org/vt.php.

8) The glass shell external surface, for example, has been flattened in order to have a constant thickness and small curves have been eliminated, in order to reduce meshing problems.

9) In this case, the model of the glass block was simplified as a sequence of parallelepiped elements.

10) As already underlined, the standard fits more suitably to flat glass, but it can be extended, with some adjustments, for the calculation of the U value also in the case of the glass block.

11) The values used are a winter external design temperature (5°C) in the city of Palermo (Italy) according to Annex 1 of D.M. 27/06/2005 and an internal design temperature (20°C) defined in DPR 412/93.

12) For the detailed description of the calculation process, refer to the paragraph 5 of the standard EN 673:2011.

13) The mean absolute temperature of the gas space, for glazing systems with more than one gas space, is calculated by means of an iteration procedure described in Annex A of EN 673:2011.

14) In other words, the gas inside the cavity is treated as a solid material, characterized by an equivalent thermal conductivity ($\lambda_{eq,s}$) that accounts for the radiative and convective parts of the heat transfer.

15) Cf. Test report n. 160673, Bellaria, Istituto Giordano s.p.a., 2002.

16) In the field of the research, where this work is inserted, different aspects regarding the mechanical performance of the thermal belt have been tested experimentally and verified analytically (cf. La Barbera, 2015; Pollicino, 2015).

17) Polycarbonate conductivity (0.12 W/mK) is lower than that of glass (1 W/mK), but it has a slightly higher emissivity (0.86 against the 0.837 of the glass). It is notably more resistant to conduction than glass, but it allows for a little more thermal energy to pass through as radiation.

18) EN 673 prescribes to provide the U value rounded to the first decimal, so that often slight differences among the thermal performance of the configurations are not evident from the final rounded value, as in this case.

19) The increase of standard glass block (GB) thickness, due to the insertion of the thermal belt, may indeed result in higher manufacturing costs and represent a sensitive change in the consolidated configuration of the product. Moreover, to maintain the thickness unvaried is useful for standardization purposes, so that 80-mm thick GB with thermal belt could be installed by using the same support elements used for “standard” GB (see also Figure 4.11, p. 219, Chapter 4).

20) This could be done either by cutting the side element of the "standard" glass shells in order to make it of the correct dimensions that allow for an overall 80-mm thickness of the product assembled with thermal belt or by providing these subcomponents of a new shape (and, thus, by modifying the molds for its manufacture accordingly) in order to avoid the additional process of the "cutting" of the glass shell and the related material scrap. Some manufacturers already provided glass shells with reduced thickness (e.g. 35 mm) that are indeed thought for cold-assembled glass block and that could be already used for the above-explained purpose.
21) The name of this product is "Energy Saving Glass Block", with a declared U value of 1.5 W/m^2K.
22) After having verified, by means of appropriate simulations, that this position determines a slightly better performance in terms of U value of the glass block, compared to the coating placed on the "warmer" side.
23) If we look at the 3D results not rounded to the first decimal (U_{air}=1.645 ≃ 1.6 W/m^2K; U_{argon}= 1.570 ≃ 1.6 W/m^2K), the difference between argon- and air-filled configurations is close to 0.1 W/m^2K, even if U values coincide.
24) Evaluated by means of Opticad software in previous works (Cappello et al., 2011).
25) The models had to be redrawn for the incompatibility of the Comsol version used in this work (4.3) with the one used back in 2010 (version 3.1).
26) Despite the less detailed characterization of the 3D models, results of 3D simulations are expected to be, in this phase, closer to the real performance of the glass blocks compared to those deriving from analyses in 2D simulative environment. However, experimental validation will allow validating this assumption.
27) Furthermore, the use of PC+aerogel sheet, instead of glass, may generate a significant increase in product economic cost, which is an aspect that needs to be considered in an overall balance.
28) The "border" of the glass block generates a continuity between the outer and the inner surface of the product and a thermal bridge in several of the analyzed configurations. When the cavity is really high-insulating (for example, it is evacuated and subdivided into chambers), this could lead to a significant worsening of the thermal insulation performance of the product with regards to its value at the center of the cavity, as it also emerges from the graphs depicting glass block thermal distribution.
29) For example, an Italian company specialized in plastic extrusion, Alfa Solare (www.alfasolare.com), has patented a novel range of bars for thermal break in aluminum window frames made of a special composition of ABS, with a thermal conductivity of 0.125 W/mK (half of that of Nylon). Moreover, in Pollicino (2015) and La Barbera (2015), different materials have been analysed in this perspective. Besides Nylon PA6 and Arnite (Polyethylene terephthalate), already used for the manufacturing of prototypes by means of milling, the study also considered other materials such as ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactide or Polylactic Acid), that could reduce the cost for prototyping since they are also commonly used in 3D printing.
30) The length of vision area perimeter (l_ψ) and the linear thermal transmittance ψ were not considered, in this phase.
31) GetData Graph Digitizer was used for graph digitalization and data extraction (http://getdata-graph-digitizer.com).
32) 15 mil (0.38 mm) thick and highly transparent PVB layer, produced by DuPont and already available in the IGDB, was used for gluing together the DSC module and the glass shell. A possible issue linked to the use of PVB regards the hot temperatures necessary for the lamination that could damage the DSC module. Other solutions for "cold" lamination have been developed and other materials have been analysed as well to overcome this problem; since this aspect is a technological aspect that does not invalidate the results of the analyses, in this phase, it has been decided to consider PVB for the lamination.
33) However, it has already been underlined that for the evaluation of glass block thermal and optical perform-

ance, the reference standards, as also indicated in glass block commercial and technical guides as well as in test reports, are those specifically developed for flat glass, e.g. EN 673:2011 for thermal transmittance and EN 410:1998 for luminous and solar characteristics. In addition, the glass block producer taken as reference in the present work adopts these standards and provides its product values of SHGC and T_{vis} that neglect the effect of glass block border between the inner and outer glass shells that form the product (Cf. SSV, 2008).

34) WINDOW also provides the thermal transmittance (U value) but only referring to the vision area. The thermal transmittance of the whole product (including glazed border), both in PV-integrated (par. 5.6.2) and thermally-optimized (par. 5.5.8) configurations, has already been analysed on 3D and 2D models by means of Comsol Multiphysics and the contribution of the border to the U value of the glass block has already been discussed in the light of these results. Their comparison with WINDOW results only regarding the vision area is useful to make additional considerations on the effect of the glass block border, enabling a full characterization of the product.

35) The WINDOW manual even suggests a method to calculate glass block thermal performance, starting from experimentally measured thermal conductance (Mitchell et al., 2013, chapter 8, p. 70).

36) The IGDB – published and maintained by LBNL – is a database collecting optical data for over 4700 glazing products. Spectral transmittance and reflectance are measured and submitted to the IGDB by the manufacturer of the glazing product subject to a careful review. WINDOW relies on input data provided by the IGDB for its calculations. However, it can also work with user-entered data.

37) As already anticipated, deeper thermal and optical analyses on three-dimensional models of the four DSC-integrated glass block configurations have been carried out by means of Zemax software to evaluate the global thermal and optical (luminous and solar) characteristics of the product. These are reported later in this chapter.

38) Inside air temperature: 24°C; Outside air temperature: 32°C; External Heat Transfer Coefficient (h_e): 23 W/m^2K; Internal Heat Transfer Coefficient (h_i): 8 W/m^2K; Direct Solar Radiation: 1000 W/m^2.

39) However, technological reasons, e.g. related to ensuring the PV-integrated glass block a better resistance to degradation and atmospheric agents, can justify preferring Configuration 3 to Configurations 1 and 2, despite the lower PV production. In this sense, prototyping and more detailed calculations could help in defining the best configuration of the DSC-integrated glass block.

40) The active area percentage should not be confused with the DSC module area, that is the ratio of the area of the DSC device by the glass block area and changes from one PV-integrated glass block configuration to another.

41) The commercially available Tech15 glass, 3-mm thick, product from the Libbey Owens Ford Company.

42) It should be said, however, that WINDOW and Optics already provide only one value corresponding to the centre of the glazing. In the case of WINDOW, it already weighs subcomponent properties.

43) The Swiss company g2energy (www.g2e.ch) is developing, in collaboration with a Swiss metallic textiles manufacturer SEFAR (www.sefar.com), a system to avoid the "separation" of the modules into thin cell strips and to obtain maximized power density as well as full module area exploitation.

44) A preliminary numerical test of Zemax model accuracy was obtained by calculating the solar transmittance of a 6-mm thick float glass sheet (according the EN 410:2011) and comparing the numerical result to the theoretical solution deducted from the direct application of analytic equations. The computation confirmed that the Zemax model was correctly tuned (Cf. Calabrò, 2014 and Di Maggio, 2014).

45) Also in these simulations, the DSC assembled at the École Polytechnique Fédérale in Lausanne and deeply discussed by Wenger et al. (2011) was used. For the purpose of the study, all the optical properties have been

obtained from published scientific papers and from product catalogues of different glass block companies, as in the analyses described in the previous paragraphs.

46) $T^*(\lambda) = e^{-\alpha z}$; where: e is Euler's number; α is the absorption coefficient at the given wavelength.

47) In particular, the change of medium, from solid to gaseous, provokes a deviation of the light-rays and may result in a drop of the power recorded by the detector.

48) Wenger's DSC is characterized by a 7.6% efficiency, but for any further calculation of the electrical power, this value – that is referred to a lab cell – had to be reduced to take into account the decrease in the conversion efficiency occurring when scaling lab cells to commercial modules; moreover, simulations were carried out by considering the whole DSC module surface as active (AA%=100%), while the actual active area of DSC typical striped configuration (capable to maximize the conversion efficiency) is smaller due to the presence of edges and spaces between the cells. Hence, a reference 5% DSC module efficiency was assumed for the calculations, which finds validation also in literature data and in the actual efficiency ranges of commercial DSC modules.

49) That in WINDOW, program based on flat glazing products, are accounted for simply by weighting the characteristics of the vision area and of the frame according to their actual area coverage.

50) However, different values of thickness can be provided by the manufacturer according to customer needs.

51) Actually, as underlined in Chapter 2, lab efficiencies for DSCs have reach notably higher values, close to 15%.

52) For this reason, further analyses are going to be performed by taking into account modules with different optical characteristics, in order to enlarge the range of possible options provided by the product.

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CHAPTER 6
Hypothesis of Application of the BIPV Glass Blocks on a Building in Palermo
Ipotesi di Applicazione dei vetromattoni BIPV in un Edificio a Palermo

ABSTRACT_ITA - *A partire dai risultati ottenuti nei capitoli precedenti, il presente capitolo si concentra sull'analisi dei benefici e delle problematiche connesse all'installazione del vetromattone integrato con moduli DSC come sub-componente dell'involucro di un edificio esistente scelto come caso studio. In particolare, l'obiettivo di tale analisi, condotta con il supporto del software per la simulazione energetica degli edifici DesignBuilder, è la valutazione delle ricadute connesse alla sostituzione dell'involucro vetrato di un edificio per uffici della città di Palermo con un nuovo involucro traslucido realizzato con pannelli multifunzionali ed assemblati a secco in vetromattoni integrati con DSC.*

L'involucro di questo edificio è attualmente costituito, su tutti e quattro i fronti, da un curtain wall in vetro. Ciò determina elevati costi di gestione, soprattutto legati al raffrescamento dell'edificio per il mantenimento del comfort indoor, specialmente durante il periodo estivo.

Dopo aver analizzato le prestazioni energetiche dell'edificio allo stato di fatto, il lavoro ha riguardato il progetto del nuovo involucro e di tutti i componenti necessari per la sua connessione alla struttura portante dell'edificio. Successivamente, le performance energetiche dell'edificio dopo la sostituzione dell'involucro sono state analizzate e messe a confronto con quelle ottenute sull'edificio allo stato di fatto. In particolare, sono state prese in considerazione due differenti configurazioni del vetromattone integrato con DSC, allo scopo di ottenere un maggiore spettro di risultati possibili.

Al di là della produzione di elettricità, in grado di soddisfare all'incirca il 10% dei consumi annuali dell'edificio, si è registrato un abbattimento significativo dei consumi energetici legati al raffrescamento degli spazi interni. In particolare, tale abbattimento si attesta fra il 20-29% ed è legata alla riduzione degli apporti esterni di calore, dovuta alla presenza delle celle solari semi-trasparenti integrate all'interno del vetromattone.

Abstract_ENG - *Starting from the results obtained in the previous chapter on the PV-integrated glass blocks, this chapter focuses on a real case evaluation, by means of the building simulation software DesignBuilder, of the benefits and issues deriving from their installation as technical elements of the building envelope. In particular, the aim of the simulations described in this chapter is to analyze the relapses deriving from the replacement of the glazed curtain wall of an office building located in Palermo (Sicily) with a new translucent BIPV envelope made of multifunctional glass block panels integrated with DSCs.*

This 11-storey building chosen as case-study is cladded by a curtain wall determining high management costs in order to maintain indoor comfort, especially during summer. This is due to the significant internal gains due to occupancy and equipment as well as to the high average temperatures and global solar radiation characterizing the city of Palermo.

After having analyzed the energy performance of the building at current state, the new building envelope has been designed, along with all the components for the connection of the glass block panels with existing load bearing structure. Subsequently, the energy performance of the building, after the replacement of the building envelope, have been analyzed and compared with those of current state. In particular, two different glass block configurations have been considered in order to obtain a wider spectrum of results.

Besides the clean electricity production — covering around 10% of building electricity needs — a significant reduction of the yearly energy consumption of the building, related to air conditioning systems, was registered, due to the shading effect and solar gain reduction provided by the semi-transparent DSC modules integrated into the glass blocks.

6.1. Introduction

In the previous chapter, the research focused on the detailed evaluation of the energy (electrical, thermal, solar, and optical) performance of the DSC-integrated glass block and on the definition of a range of possible configurations. Within this range, building planners and energy/environmental consultants can configurate the most adapted DSC-integrated glass block to respond to specific needs related to the characteristics of each project and context of installation (e.g. climate, possible orientation of the building surfaces, light transmission and thermal insulation properties required to the envelope, occupants' activities within the building, and so on...).

The final part of the thesis will focus on a real case evaluation — by means of building simulation software DesignBuilder[1] — of the benefits and issues deriving from the installation of the building product introduced and analyzed in the previous chapters, as technical element of the building envelope. In particular, the aim of the simulations described in this chapter is to analyze the possible benefits and issues deriving from the replacement of the glazed curtain wall of an office building located in Palermo (Sicily) with a new translucent BIPV envelope made of multifunctional glass block panels integrated with DSCs[2].

The energy performance of the building, before and after the replacement of its envelope, will be analyzed with specific focus on the thermal performance, and the results of the energy performance simulations on the current state will be compared with those deriving from the installation of the new envelope made of BIPV glass block panels. These translucent panels, indeed, are expected to generate positive relapses, not only linked to the electricity production, but also in terms of energy-savings due to the thermal insulation and solar radiation control provided. The benefits linked to these latter aspects are not easy to be quantified and the case study building, which will be introduced and described more in depth in the following paragraph, was taken as a pretext for this purpose. The eventual problems deriving from this integration will be discussed as well.

6.2. The Case-study Building in Palermo

The object of the analyses is an office building located in Palermo, dating back to the late 70s and the early 80s of the last century. It is located in a highly built area of the city and it hosts today the headquarters of the Regional Department of the Energy and of the Public Utility Services[3].

The building consists of 11 levels above the ground and two underground parking levels, for a total area of approximately 14,000 square meters. The plan of the building is rectangular, slightly rotated (35° anti-clockwise) with respect to north-south axis. The longer sides are oriented towards south-east and north-west and, consequently, the shorter sides are oriented towards north-east and south-west.

The ground floor is provided with two separated entrances and, in the upper levels, the access to the offices, which are disposed along the perimeter of the building, occurs through a long corridor that runs lengthwise through the entire building.

Photo 1 - Views of the building

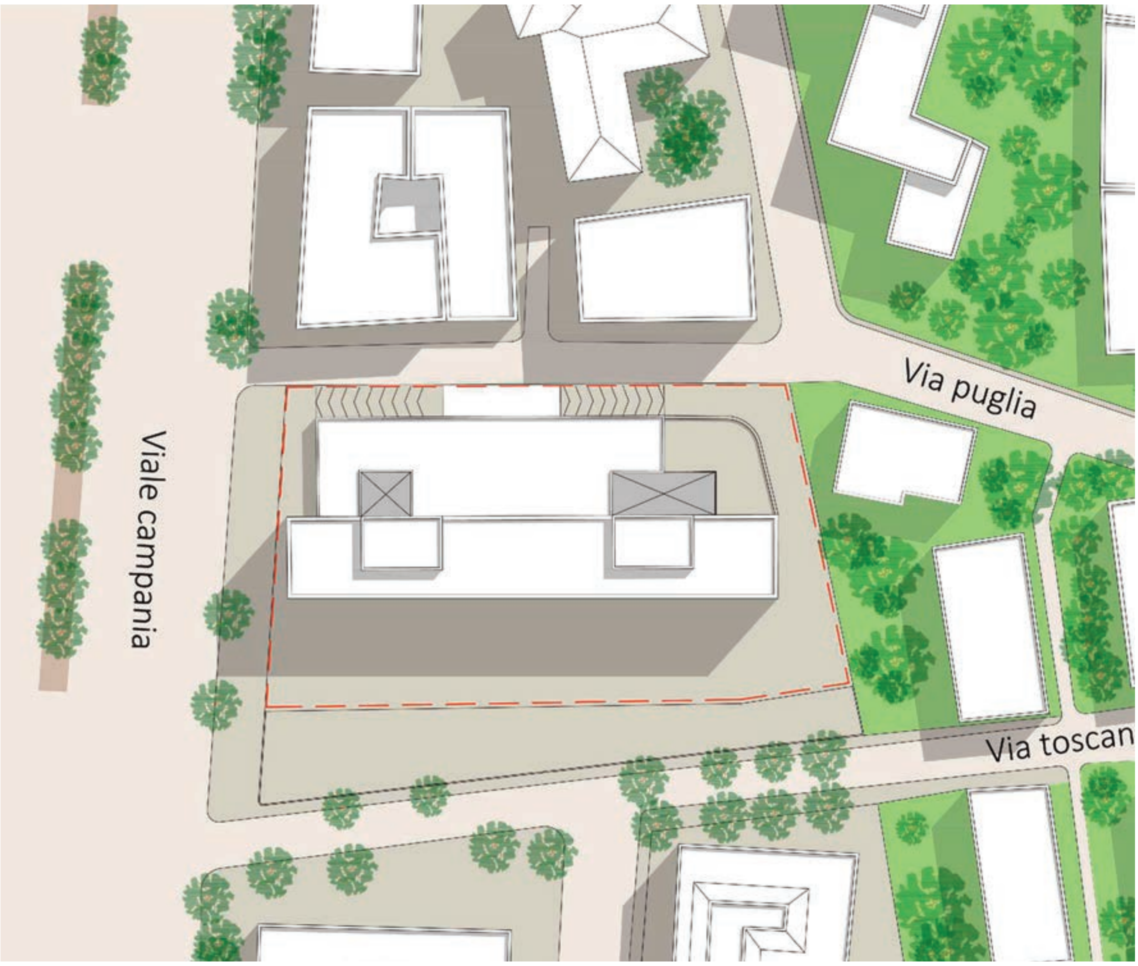
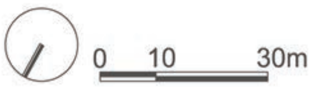


Figure 6.1 - Roof plan including the surroundings (Milia, 2015; Tutone, 2015)



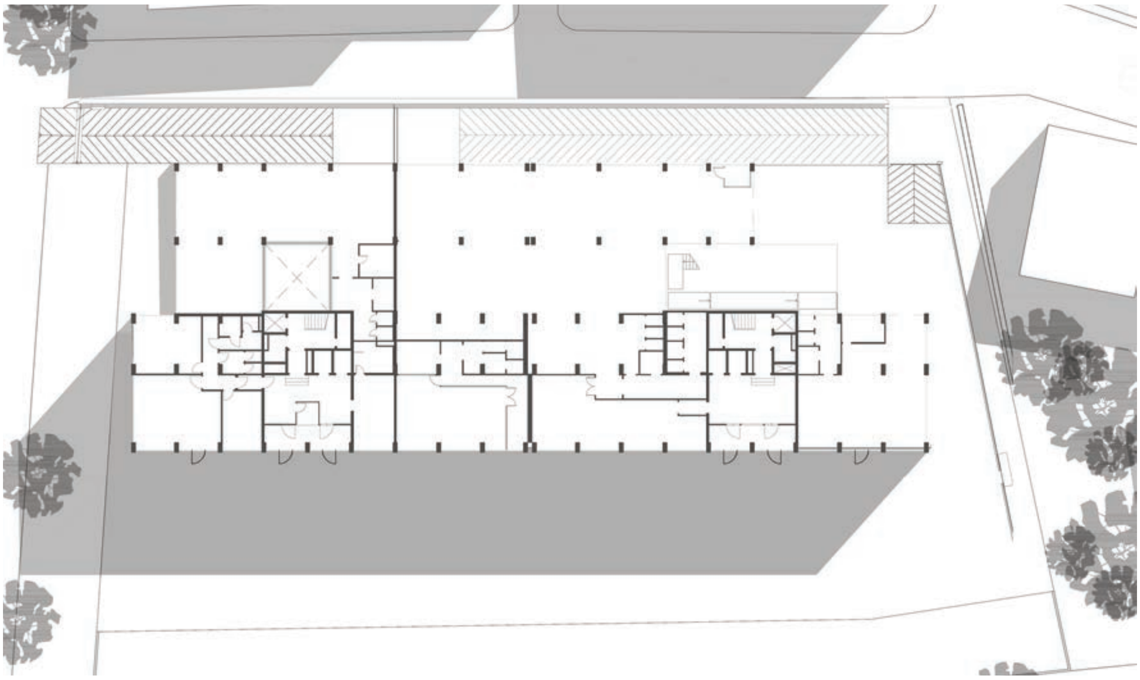


Figure 6.2 - Ground level plan including the surroundings (Milia, 2015; Tutone, 2015)

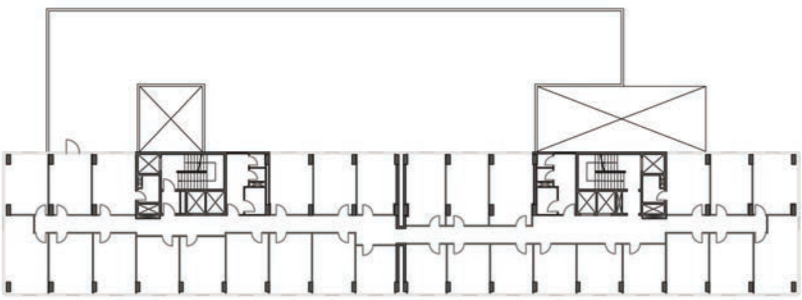


Figure 6.3 - Plan of Level 1 (Milia, 2015; Tutone, 2015)

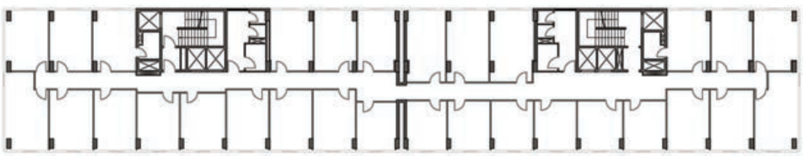


Figure 6.4 - Plan of the Typical Level (Milia, 2015; Tutone, 2015)

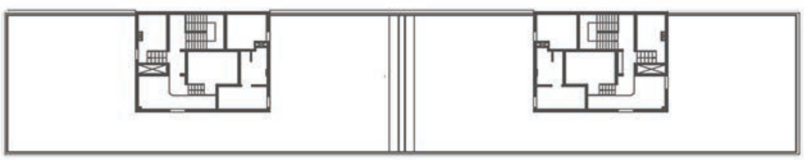


Figure 6.5 - Plan of Level 11 (Milia, 2015; Tutone, 2015)

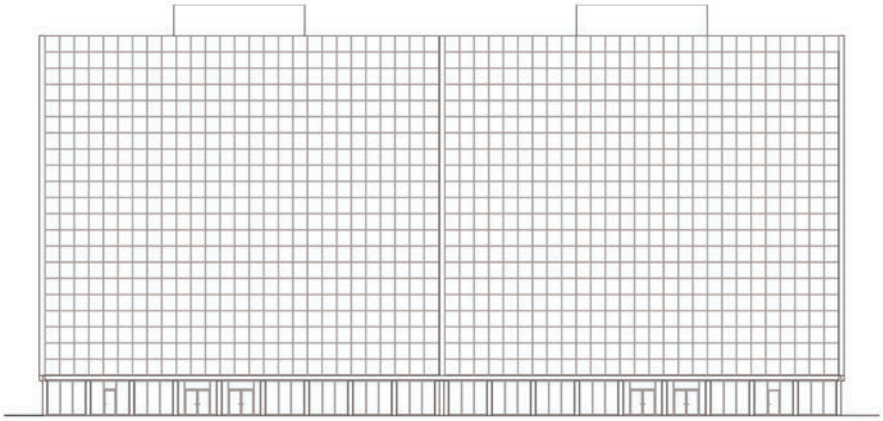


Figure 6.6 - NW façade (Milia, 2015; Tutone, 2015)

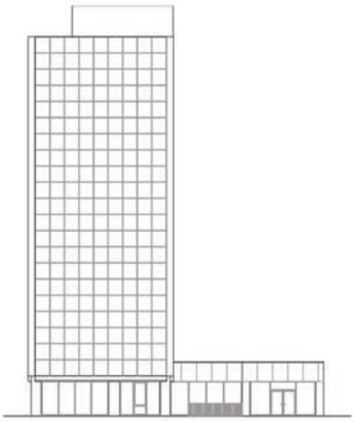


Figure 6.7 - SW façade (Milia, 2015; Tutone, 2015)

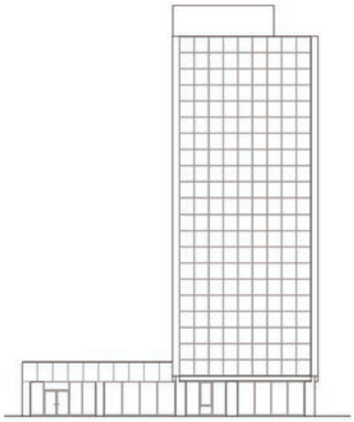


Figure 6.8 - NE façade (Milia, 2015; Tutone, 2015)

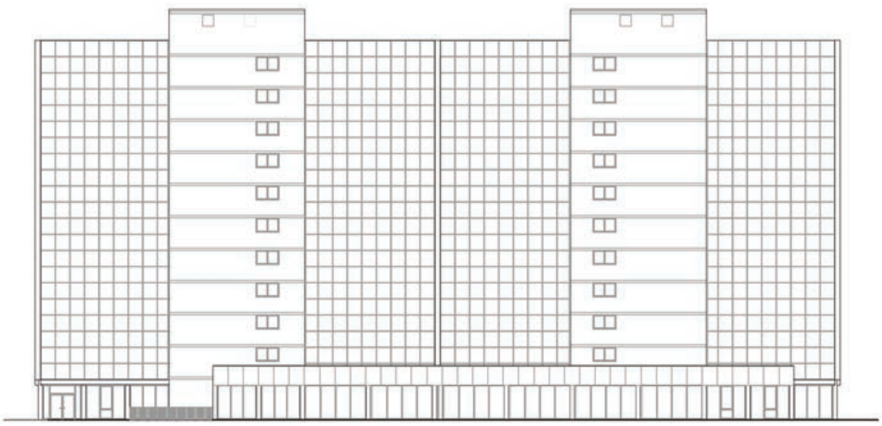


Figure 6.9 - SE façade (Milia, 2015; Tutone, 2015)

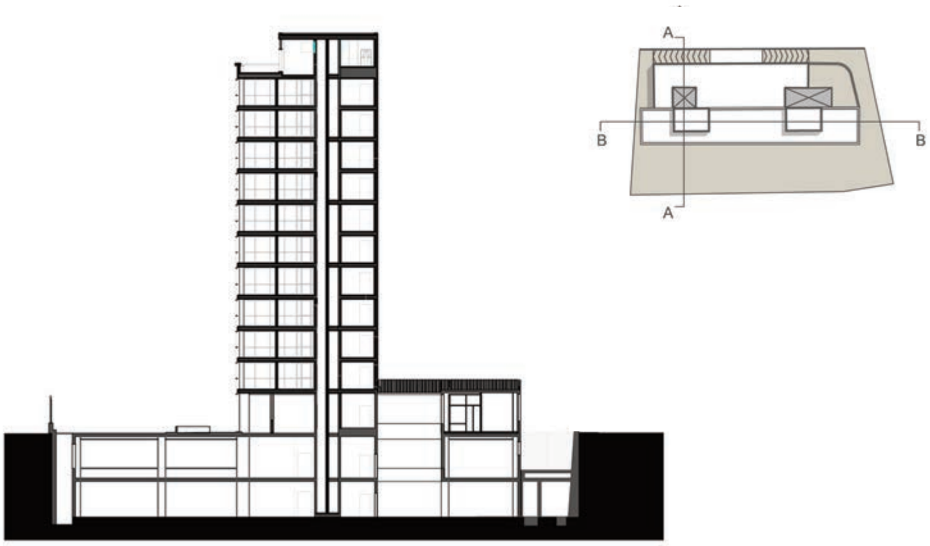


Figure 6.10 - Cross Section AA (Milia, 2015; Tutone, 2015)

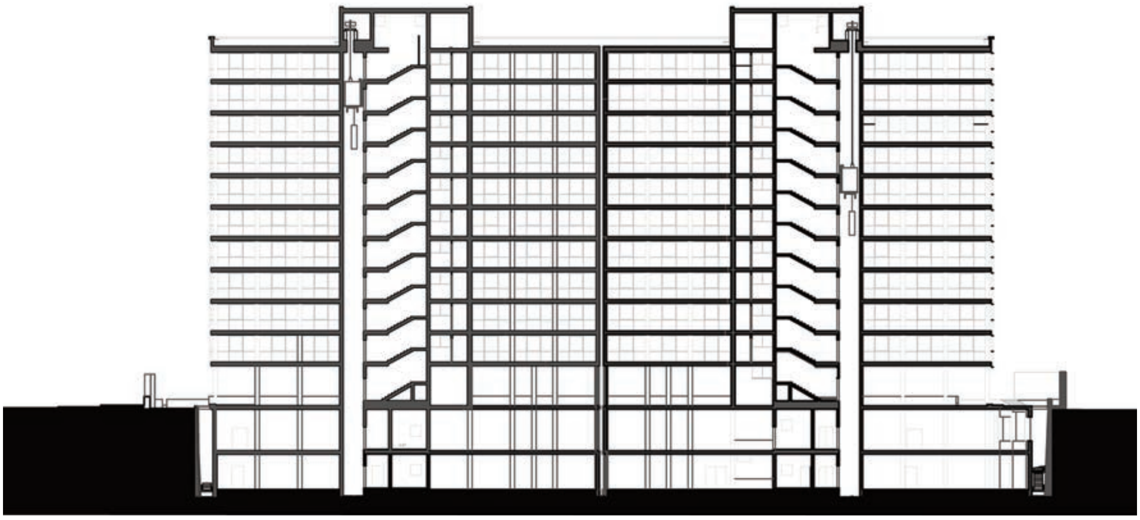


Figure 6.11 - Cross Section BB (Milia, 2015; Tutone, 2015)

The office rooms have an average area of 21 square meters and each is provided with one openable window (Figure 6.12). In every office, a furniture element is installed right below the opening in order to conceal the heat pump terminal. Warm or fresh air coming from the system is supplied to the office spaces by means of a ventilation grill, placed on the upper side of the furniture element. Offices are normally occupied by two or three employees. It is worth to mention that the inter-floor distance is very small and, indeed, it does not overcome 3 meters, resulting into a net height of the indoor spaces of 2.7 m.

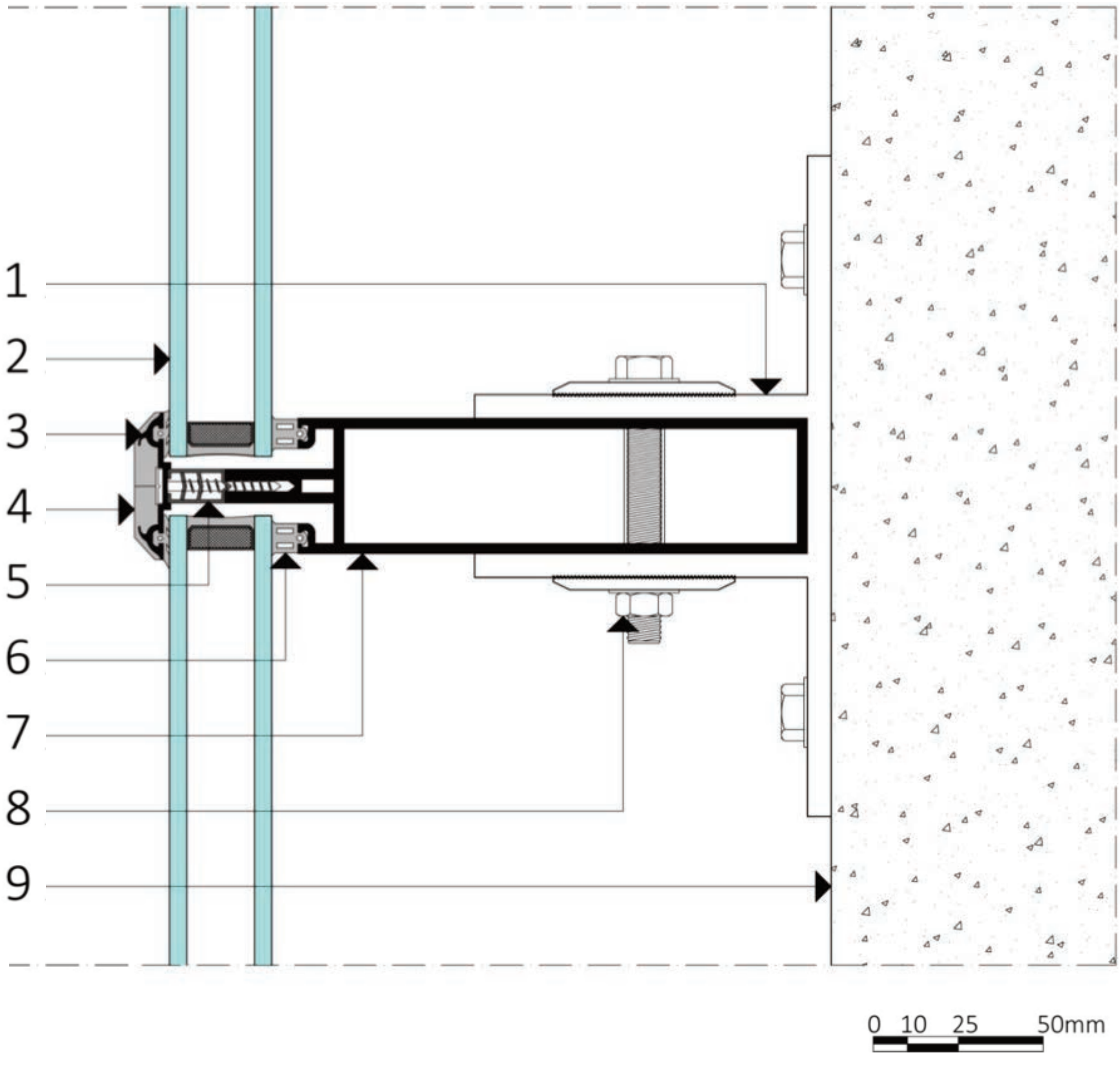
Figure 6.12 - Cross Section and Plan of the Typical Office (Milia, 2015; Tutone, 2015)

At present, the offices are characterized by internal curtains, manageable by users, for sunlight attenuation. It should be noted, however, that this study has not focused on the analysis of the daylighting performance of the building, whereas it has been addressed to the evaluation of its energy consumption related to heating, cooling and ventilation and, thus, on the thermal rather than on the visual comfort[4]. The building, indeed, is characterized by quite high management costs for the maintenance of indoor comfort, especially for cooling. De facto, the building is located in a warm climate context. Moreover, regardless of the climate context, as several authors underlined, the problem of the cooling is a great problem, especially in office buildings, where it represents the main factor of energy consumption due to the heat emitted by people, by terminals, by artificial lighting (Schittich, 2003).

Photo 2, 3 - View of the curtain wall and of the curtains from inside the offices

6.2.1. The Building Envelope at Current State

The building envelope is constituted, almost entirely, by a glazed curtain wall provided with an aluminum post-and-rail framing system. The only exception is represented by the spaces for the vertical connections (stairs and elevators) within the building: these are indeed cladded by concrete elements. The vertical elements of the aluminum framing of the curtain wall are mechanically fixed to the building structure in reinforced concrete, by means of steel brackets. A cross section of the façade system is reported in Figure 6.12.



LEGEND
1. *Supporting element,* Aluminum bracket
2. *Infill element,* Double-glazing 4+20+4
3. *Fixing element,*
4. *Protection element,* Silicon joint cover
5. *Insulating element,* Polyamide bar
6. *Air/water tightness element,* Silicon gasket
7. *Supporting element,* Hollow steel profile
8. *Fixing element,* Bolt
9. *Load-bearing element,* Concrete beam

Figure 6.12 - Detail of the vertical cross section of the Building Envelope system at current state

The glass infills are double-glazing elements, with an internal 20mm thick cavity, filled with dry air, as it is possible to see from Figure 6.12.

The glass panes are 4mm thick and one of them is provided with a low-emissive coating, able to reduce the thermal transmittance of the component.

The two glasses were selected withing the International Glazing DataBase (IGDB) and then utilized for the analyses. The main spectral and thermal properties are reported detailedly in Table 6.1.

	Low-E glass (Layer 1)	Clear glass (Layer 2)
Thickness (mm)	4.000	4.000
Thermal conductivity (W/mK)	1.000	1.000
Solar Transmittance	0.620	0.816
Solar Reflectance, front	0.075	0.075
Solar Reflectance, back	0.075	0.075
Visible Transmittance	0.847	0.892
Visible Reflectance, front	0.081	0.081
Visible Reflectance, back	0.081	0.081
Infrared Transmittance	0.000	0.000
Front emissivity	0.840	0.840
Back emissivity	0.100	0.840

Table 6.1 - Properties of glasses composing the double-glazing at current state, as required by DesignBuilder

The above-introduced geometrical and physical properties related to the two glasses and to the inner air cavity were entered into DesignBuilder software, in order to characterize the glazing system for the simulations.

The global thermal and optical performance parameters of the glazing system as calculated by WINDOW, are the following: U value: **1.9 W/m²K; g-value: 58.5%; T_{vis}: 0.761**.

As regards the framing, its geometry was modeled and simulated by using the Therm software (LBNL, 2014b). An external temperature of 5°C and and internal temperature of 20°C were set. The resulting U value of the frame (2.9 W/m²K) was then entered into DesignBuilder for the launch of the simulations of the current state[5].

6.3. Definition of the virtual model of the building and methodology

In order to run the energy performance simulations by means of DesignBuilder software on the analyzed building, both at the current state and with the new glass block façade configuration, a virtual three-dimensional model of the building was defined[5] and appropriately localized in the city of Palermo.

This phase was undertaken by referring to the normative framework provided by the Italian Standard UNI TS 11300-1:2008 and can be divided into three sub-phases:

- subdivision of building indoor spaces into "thermal zones", as defined in the above-cited standards[6];
- characterization of the stratigraphy of all surfaces delimiting the thermal zones (materials, properties, etc.);
- definition of the indoor comfort characteristics, as prescribed by the technical standards.

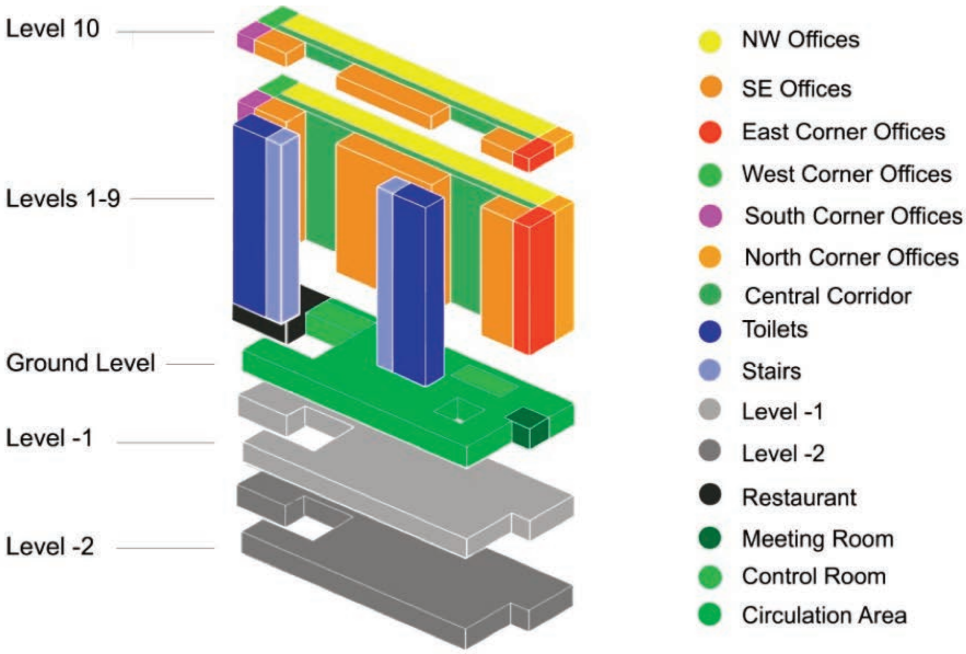


Figure 6.13 - Illustration of the thermal zones individuated in the building

The building was subdivided into 30 thermal zones, which were individuated according to their utilization and position in the building (Figure 6.13).

The surfaces delimiting the thermal zones were characterized in terms of stratigraphic composition, materials and related thermal as well as optical properties. For each thermal zone, occupancy density (people/m^2), periods of users' presence (considering, e.g., the building frequented from monday to friday, from 9 a.m. to 6 p.m.) and heat gains related to occupancy, equipment and lighting systems were defined by taking into account both indications from the above-cited standards as well as default values provided by the software.

Based on the indications of the DPR 412/1993 regarding office buildings situated in Palermo (climate zone B), the indoor comfort temperatures, used as reference for the simulations, were assumed equal to 20°C during wintertime and to 26°C during summertime.

This preliminary activity of definition of the model for this building (thermal zones, activities, material properties, indoor comfort conditions, and so on…) does not change between the simulations of the building at the current state and after the reconfiguration of its envelope. The only data that change are those related to the building envelope. The main aim of the analyses is indeed to test the benefits related to the replacement of the existing building envelope with the multifunctional DSC-integrated glass block components.

The system for heating and cooling of the building consists of a centralized plant with individual terminals in each office. The capacity of the system has been defined by taking into account the prescriptions of the standard, through the execution of:

1) Steady-state winter simulation (*Heating Design*);

2) Semi-static summer simulation (*Cooling Design*);

Afterwards, it is possible to assess the real performance of the building, by means of:

3) Dynamic building simulation.

Steady-state winter simulation (Heating Design):

simulation in stationary conditions for the sizing of the heating system and for the calculation of the heating load needed to maintain a prescribed indoor comfort temperature (20°C), balancing the heat losses through the elements of the building fabric as well as those due to the air infiltration[7] across the building envelope. Heated zones are heated constantly to achieve the heating temperature set point. Calculations are conducted in the most unfavorable winter conditions, characterized by:

- a constant steady-state external temperature, which is set to the average of the minimum seasonal temperatures for the considered climate zone (5°C in this case);
- the absence of internal heat gains (related to e.g. occupancy, equipment and lighting);
- the absence of solar heat gains;
- heat conduction and convection between thermal zones at different temperatures.

A safety factor (design margin) is used and is set to 1.8, meaning that the plant size is based on the calculated heat loss plus 80% so to provide an additional heating capacity that is needed when the heating system has been switched off for extended periods (e.g. during weekend or night). This effectively reduces the pre-heating time required to reach heating set point.

Semi-static summer simulation (Cooling Design):

simulation taking into account a typical summer day for the calculation of the cooling load needed to maintain the prescribed indoor comfort temperature (26°C) in the most unfavorable summer conditions, characterized by:

- climatic conditions of a typical summer day (July 15th, in the area of Palermo);
- the presence of solar heat gains;
- the presence of internal heat gains (related to e.g. occupancy, equipment and lighting);
- the absence of natural ventilation;
- heat conduction and convection between thermal zones at different temperatures.

Differently than in the winter heating design calculation, the simulation is semi-static because it takes into account the hourly variations (of temperature, solar radiation, and so on) occurring during a typical summer day. The cooling system capacity is obtained by taking into account a safety factor of 1.3.

The two above calculations are useful to size the heating and cooling system capacity, allowing for some preliminary considerations on the cost-benefit performance of an envelope solution rather than another (that e.g. differ in terms of thermal insulation). Indeed, for example, a smaller capacity for the heating plant translates into lower installation costs at a first stage[8]. They also help to individuate the main causes of heat gains and losses and thus to identify potentially weak points, by looking separately at the thermal zones and at the various elements of the building fabric; hence, they can enable to modify accordingly the features of the building envelope. Once the heating and cooling system capacity has been defined, dynamic simulations can be executed, in both summer and winter conditions, in order to understand the real behavior of the building during longer periods. Dynamic simulations are based on Palermo climatic features, as indicated in the corresponding weather file[9] referred to the so-called typical average year.

Dynamic building simulation:

Regarding the dynamic simulations at current state in the winter period, in a first phase the analyses focused on a specific day representative of typical winter conditions in the city of Palermo (January 3rd) and were followed by a more extended evaluation on medium- and long-term building energy performance, referred to typical winter week, from January 1st to 7th and to a 4-month heating period. In particular, the reference standard UNI TS 11130-1 prescribes — for building of the climate zone B as in the DPR 412/1993 — a simulation period of 4 months, from December 1st to March 31st.

Summer performance was assessed by following the same methodology and, in particular, by taking into account a typical summer day (July 15th), a typical summer week (from July 8th to 14th) and a 4-month cooling period[10] , which has been set from June 1st to September 30th.

As already highlighted, this work takes this building — one of the few entirely glazed buildings in the city of Palermo — as a pretext to evaluate the potential benefits of the novel building and PV solution described and analyzed in the previous chapters, both in terms of possible energy saving as well as of energy production.

The building was treated as if it was a new construction: indeed, it has not been possible, at least not in this first stage, to calibrate the virtual model of the building according to its real utilization and occupants' behaviors and, therefore, it was not possible to relate the actual energy consumption with the ones deriving from the simulations. The centralized heating and cooling plant — whose capacity and characteristics were not known — was dimensioned, both at current and "retrofitted" state, as if we were dealing with a new construction, complying with all the regulatory indications. However, this allows for an "ideal" comparison between the current technical solution for the building envelope with the new DSC-integrated glass block components but, without an accurate work of calibration of the model, it does not consent to relate the results of the simulations to the real energy consumption and performance of the building (significantly dependent upon occupants' behaviour). This aspect, in the end, is not the objective of this work but it can represent a possible future development of the research and, together with an in depth cost-benefit analysis, it is particularly necessary if a retrofit operation of the building is intended to be undertaken.

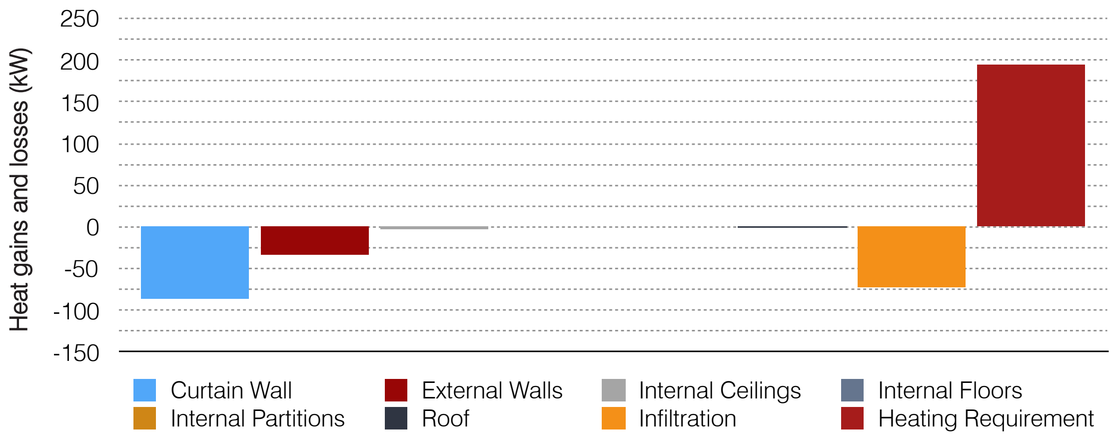
6.4. Energy Performance Simulations of Current State

Simulations on the current state were run first in order to understand the behavior of the modeled building with the current envelope solutions. The methodology described in the previous paragraphs was used, starting from the steady-state winter design calculation.

6.4.1. Heating Design calculation

As regards the heating design calculations on the current state, the software provides the heating power required to maintain the design temperature in the unfavorable winter conditions described above. The heat losses related to the various components of the building fabric (glazed curtain wall, concrete walls, roof, internal partitions, etc.) are provided as well, referring both to the different thermal zones and to the whole building performance. The heat losses deriving from air infiltrations through the envelope are also indicated.

Results are reported in the following graph (Figures 6.14) and table (Table 6.2), where the total heating capacity is indicated. This latter is obtained by multiplying the total heating requirement (193.58 kW) by the safety factor (1.8) introduced in paragraph 6.3.1 and is equal to 348.45 kW.



Curtain Wall	-85.48 kW
External Walls	-32.28 kW
Internal Ceilings	-2.88 kW
Internal Floors	-0.05 kW
Internal Partitions	0.00 kW
Roof	-1.72 kW
Infiltration	-71.22 kW
Heating Requirement	193.58 kW

Figure 6.14 - Heat gains (>0) and losses (>0)

Level	Zone	Operating temp. (°C)	Heat loss (kW)	Heating Capacity (kW)
Floors 1-9	Offices West corner	18.68	6.73	12.11
	Offices South corner	18.62	5.62	10.12
	Offices SE (group 3)	18.96	8.49	15.28
	Corredor	19.39	15.85	28.53
	Toilets (west)	18.50	7.20	12.96
	Offices SE (group 2)	19.22	19.88	35.78
	Toilets (east)	18.51	7.12	12.82
	Offices SE (group 1)	18.97	8.41	15.14
	Offices East corner	18.65	6.48	11.66
	Offices NW	19.24	51.94	93.50
	Offices North corner	18.63	5.29	9.53
10th Floor	Offices West corner	18.53	0.84	1.51
	Offices South corner	18.47	0.70	1.26
	Offices SE (group 3)	18.86	1.03	1.85
	Corredor	19.31	1.94	3.49
	Offices SE (group 2)	19.13	2.41	4.34
	Offices SE (group 1)	18.88	1.01	1.81
	Offices East corner	18.22	0.98	1.76
	Offices NW	19.14	6.4	11.53
	Offices North corner	18.45	0.67	1.21
Ground Floor	Control Room A	19.26	1.10	1.98
	Entrance	18.64	25.24	45.42
	Meeting Zone	18.56	1.20	2.16
	Toilets (east)	19.19	0.49	0.88
	Control Room B	19.23	1.12	2.02
	Toilets (west)	18.40	0.97	1.75
	Bar	18.22	4.47	8.05
	Total		**193.58**	**348.45**

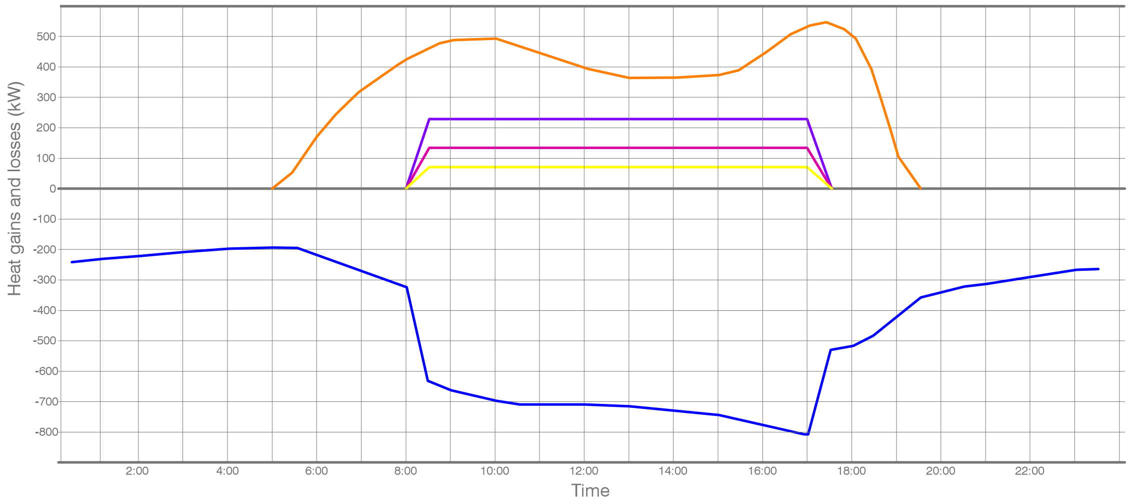
Table 6.2 - Summary of the heating design calculation with indication of the heating design capacity of the system

6.4.2. Cooling Design calculation

Speaking of the cooling design calculation on the current state, taking into consideration the hourly variations that occur during a typical summer day (July 15th) in the climate zone of Palermo, DesignBuilder allows calculating the cooling power needed (i.e. the heat that has to be subtracted) to maintain the design temperature during the occupancy period. During the whole day, the outside dry-bulb temperature is above the comfort 26°C established by the standard and reaches a peak at around 2 pm.

In Figures 6.15 and Table 6.3 are reported the results of current state cooling design calculation: heat losses and gains during the day are indicated as well as the peak cooling load. Overall, the total cooling design capacity, obtained by multiplying the total cooling requirement (903.66 kW) by the safety factor 1.3 introduced in paragraph 6.3.1, is 1,174.79 kW.

Comparing the results of the Heating and Cooling Design calculations, it is possible to see how cooling requirements are three times bigger than the heating-related ones. This was expectable, due to building's climate context, characterized by high summer temperatures and elevated solar radiation levels, and due to the characteristics of the envelope, made of high solar transmission glass. Hence, measures for a relevant reduction of the solar and heat gain through the glazed envelope could help significantly improve building energy performance. However, it should also be underlined how, besides the heat gain through the glazed envelope, a relevant role in the value of cooling requirements is linked to the heat gain due to the office equipment.



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Lighting gain (kW)	0.00	0.00	0.00	0.00	71.97	71.97	71.97	71.97	0.00	0.00	0.00
Equipment gain (kW)	0.00	0.00	0.00	0.00	229.6	229.6	229.6	229.6	0.00	0.00	0.00
Occupancy gain (kW)	0.00	0.00	0.00	0.00	136.9	136.9	136.9	136.9	0.00	0.00	0.00
Solar gain (kW)	0.00	0.00	167.4	424.3	489.4	395.1	360.6	438.8	505.3	0.00	0.00
Cooling Requirement (kW)	-199.7	-168.5	-152.1	-229.6	-615.0	-662.0	-685.1	-712.9	-714.5	-401.6	-189.5

Figure 6.15 - Cooling design calculation: heat gain (>0) and losses due to cooling (<0) on typical summer day July, 15th

Level	Zone	Peak cooling time	Max operating temp (°C)	Peak cooling (kW)	Design capacity (kW)
Floors 1-9	Offices West corner	17:00	32.4	62.24	47.87
	Offices South corner	17:00	32.0	46.82	36.01
	Offices SE (group 3)	11:30	28.6	39.21	30.16
	Corredor	17:00	27.3	54.32	41.79
	Toilets (west)	17:00	28.0	15.32	11.78
	Offices SE (group 2)	12:00	28.7	236.86	182.20
	Toilets (east)	17:00	28.0	15.45	11.88
	Offices SE (group 1)	11:30	28.7	40.27	30.98
	Offices East corner	09:00	31.9	53.45	41.12
	Offices NW	17:00	28.5	287.01	220.78
	Offices North corner	09:00	31.4	39.02	30.02
10th Floor	Offices West corner	17:00	35.5	10.84	8.34
	Offices South corner	16:30	34.4	7.65	5.88
	Offices SE (group 3)	11:30	29.6	5.85	4.50
	Corredor	17:00	27.5	6.76	5.20
	Offices SE (group 2)	11:30	29.4	16.72	12.86
	Offices SE (group 1)	11:00	29.8	6.13	4.71
	Offices East corner	09:00	34.8	9.32	7.17
	Offices NW	17:00	29.5	45.17	34.75
	Offices North corner	08:30	33.8	6.53	5.02
Ground Floor	Entrance	15:00	28.9	4.92	3.78
	Toilets (west)	17:00	29.8	119.96	92.27
	Bar	09:30	31.7	8.43	6.48
	Meeting Zone	17:00	27.5	1.41	1.09
	Control Room A	17:00	27.6	4.32	3.32
	Toilets (east)	17:00	27.8	1.74	1.34
	Control Room B	17:00	32.1	29.07	22.36
	Total			903.66	1174.79

Table 6.3 - Summary of the cooling design calculation indicating, for each zone, the resulting cooling design capacity of the system, as well as the time of peak cooling and the maximum operating tempeature

6.4.3. Dynamic simulations

After having considered the behaviour of the building in the two most unfavourable winter and summer conditions, the dynamic simulations are now run in order to understand the actual behaviour of the building over more extended periods.

6.4.3.1. Winter analyses

As regards the winter performance of the building, the analysis of a typical winter day (January 3rd), is characterized by lower values in terms of solar gain transmitted across the envelope in the current state, with a peak of approximately 450 kW (Figure 6.16a).

The heat gains associated to the occupation and utilization of the building do not change from summer situation, because the number of employees accessing the building is assumed constant regardless of the time of the year. Looking at the graph depicting the behaviour of the building on this typical winter day, it is possible to see that the building needs some heating during the early morning and night hours (pre-heating, mainly); nevertheless, the most relevant fact is that, although a winter day is simulated, cooling is required during occupation hours.

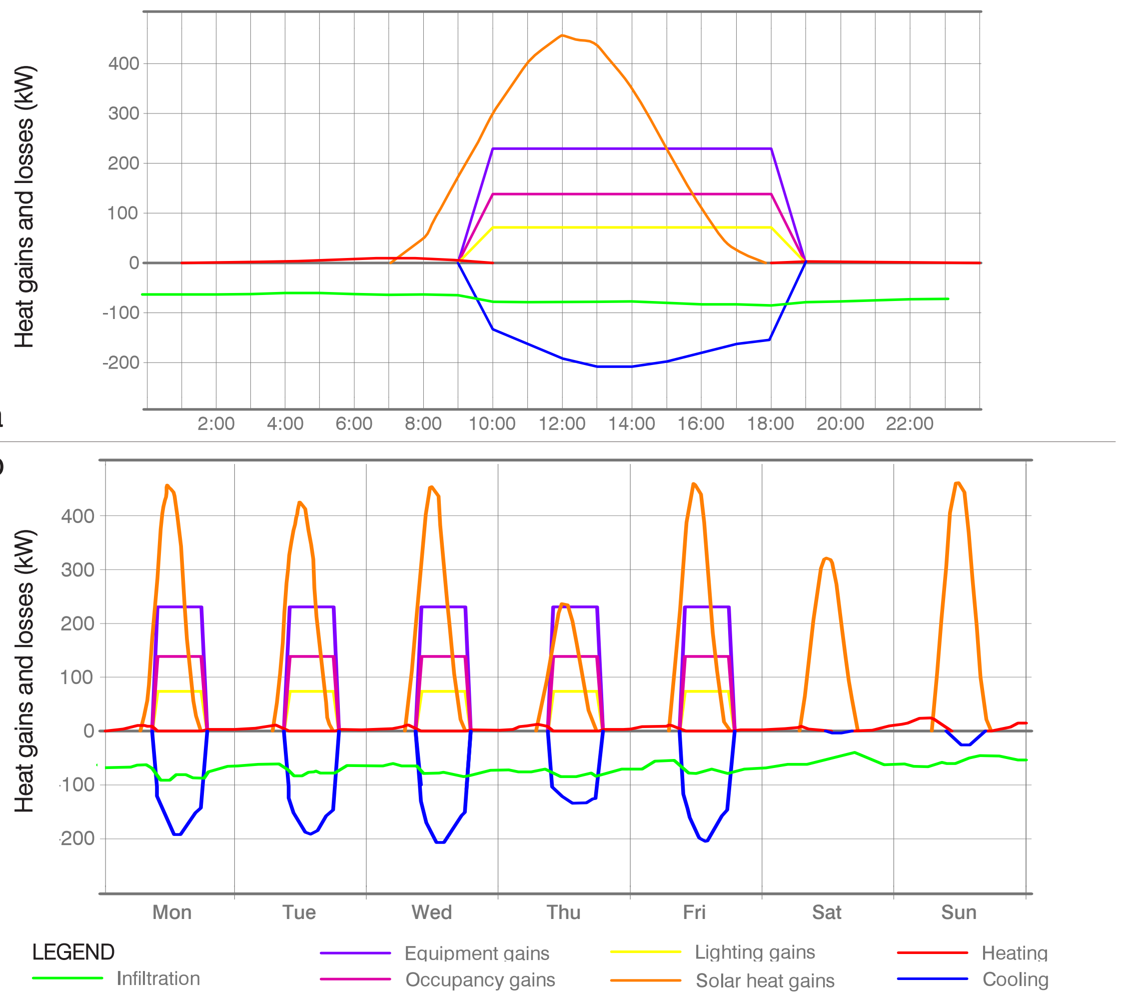
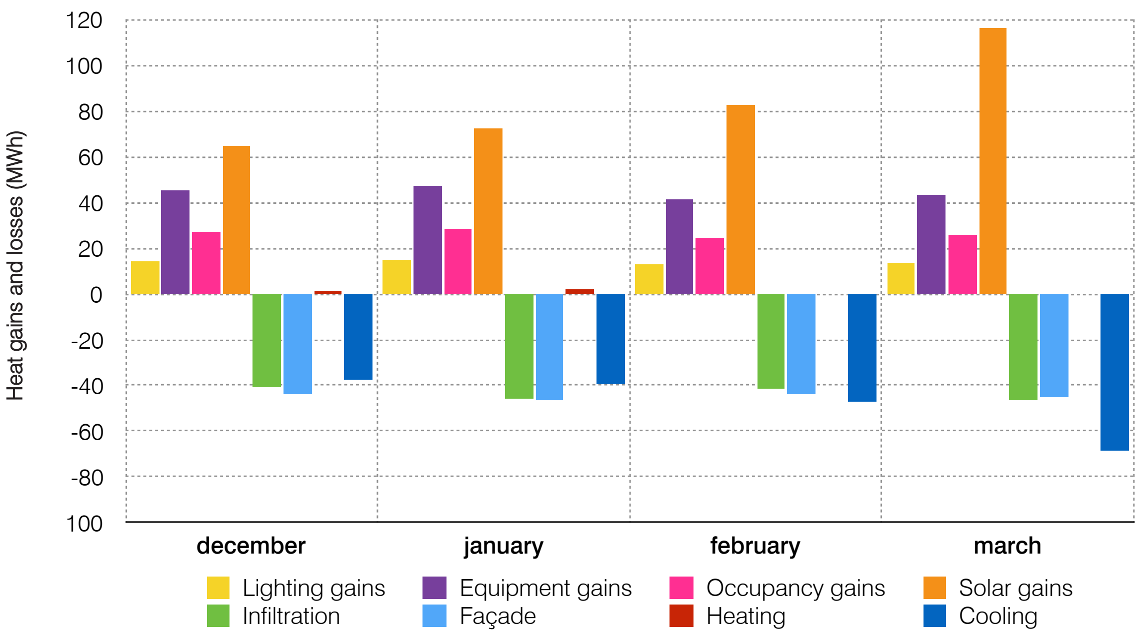


Figure 6.16a - Energy performance of the building on the current state for the typical winter day (January 3rd)
Figure 6.16b - Energy performance of the building on the current state for a representative winter week

This is due to the high levels of solar radiation and mild temperatures characterizing Palermo as well as the relevant heat gains associated to occupancy and equipment.

As regards the typical winter week (January 1st-7th, Figure 6.16b), it is possible to note the same behaviour. During weekend, when the building is not occupied, the cooling load decreases significantly; at the same time, there is a certain increase in the heating load since all heat internal gains related to the building use are not accounted for. During daily hours, when solar radiation strikes the building envelope at its peak and all internal gains are accounted, the heating requirement gets to or close to zero, both in the weekend and weekdays. During the whole winter week, the infiltration represents a heat loss factor (varying below 100 kW): this is an advantage during the cooling hours, but at the same time implies a certain increase in the heating requirement in the early morning and night hours.

Passing to the 4-month simulation, a similar behaviour can be registered. De facto, the evaluated requirements in terms of cooling are higher than those related to heating, despite the winter season. Slight changes occur from one month to the others mainly due to the variation of the solar gain through the building skin, depending on the atmospherical conditions, sun rays inclination and environmental temperatures (Figure 6.17).



	december	january	february	march	TOTAL
Lighting gain (MWh)	14.25	14.90	12.95	13.60	55.70
Equipment gain (MWh)	45.45	47.52	41.32	43.39	177.68
Occupancy gain (MWh)	27.11	28.35	24.65	25.88	105.99
Solar gain (MWh)	64.58	72.42	82.66	116.17	335.83
External Infiltration (MWh)	-40.79	-45.82	-41.03	-46.38	-174.02
Façade (MWh)	-44.04	-46.69	-43.86	-45.44	-180.03
Heating Requirement (MWh)	1.32	1.71	0.43	0.13	3.59
Cooling Requirement (MWh)	-37.33	-39.21	-46.97	-68.65	-192.16

Figure 6.17 - Overall monthly amount of heat gains and losses

For example, basically no heating is required in March, due to an overall solar gain of 116 MWh, coupled with warmer temperatures compared to the previous months. In January, instead, the biggest amount of heating among all winter months is required (1.71 MWh, that is lower than the cooling requirement of the building, accounted during the same month).

The difference in the heat gain due to occupancy, equipment and lighting are very small among the various months[11]. However, they altogether represent from 42% (in March) to 57% (in December) of the total heat gain (system heating excluded). Along with the solar gain through the building envelope, they are responsible for the large cooling requirements of the building, which amounts to 192.16 MWh. The overall winter heating requirement is significantly lower and equal to 3.59 MWh.

It should be noted how relevant is the external infiltration for the reduction of the energy requirement for cooling the building. The external infiltration indeed has values comparable to the monthly cooling requirement and it even overcomes it in December and January. This theoretically means that without the infiltration (which, however, is needed for reasons related to occupants' health and indoor air quality), the cooling requirement, in December and January would be more than doubled. A contribution of the same magnitude can be acknowledged to the thermal exchanges occurring through the façades: this is a positive aspect in this building that, even in winter, when outdoor temperatures are lower than indoor ones, mainly needs to be cooled off.

6.4.3.2. Summer analyses

The overall energy performance of the building in terms of energy gains and losses, resulting from the simulations on the typical summer day (July 15th) and of the typical summer week (July 8th-14th) are shown in the graphs of Figures 6.18a and 6.18b respectively.

From the graphs, it is possible to note how the solar gain transmitted through the existing curtain wall reaches a peak above 500 kW and how, in general, during the working hours stands above 300 kW. During the occupation hours, from 9 a.m. to 6 p.m., relevant heat gains, associated to people in the building, office equipment and lighting systems, can be observed as well, but it should be underlined that they are identical to those accounted for in winter simulations. In order to maintain the previously specified indoor comfort conditions and achieve the Energy Balance, the peak requirement of over 600 kW is determined in the current state for the cooling of the building. In particular, it occurs in the afternoon, at 4 p.m.

Taking into account a typical summer week, a similar behaviour as above is registered during the weekdays, whereas in the weekend – when users do not occupy the building and there is not any of the internal gains – a notable drop in cooling load occurs.

Looking at the external infiltration, it is evident that it represents a benefit in terms of cooling only during some hours of the day (in particular, in the night and in the early morning). In these cases, however, its effect is really negligible compared to the amount of cooling required by the building during the day and to the results obtained in winter evaluations, where the infiltration has a more relevant effect (as well as always beneficial in terms of cooling).

In Figure 6.19 are reported the results of the 4-month summer simulations, from June to September, where main sources of heat gain and loss are indicated. As expected, during summer months, when the solar gain through the building envelope and temperatures are

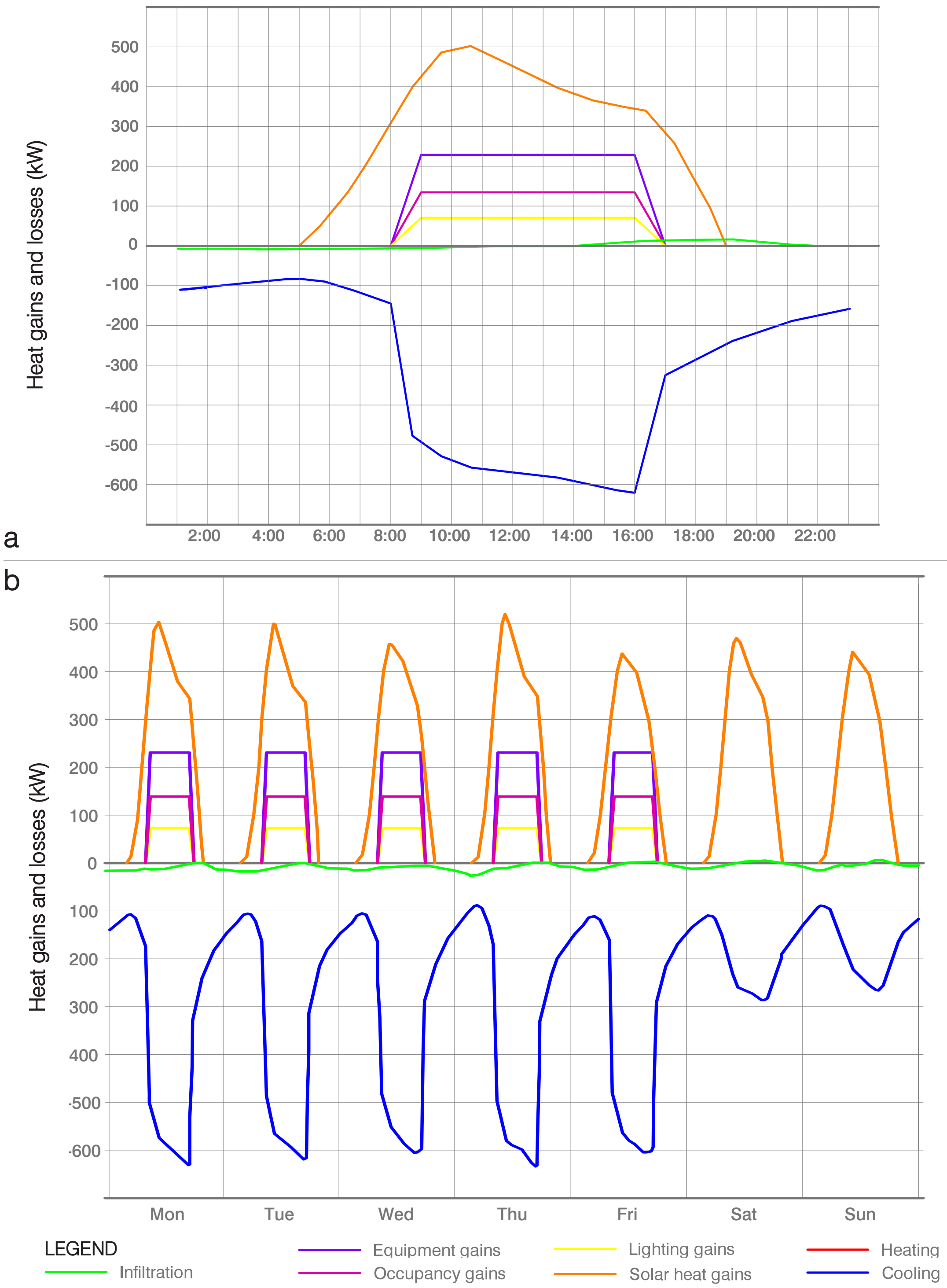
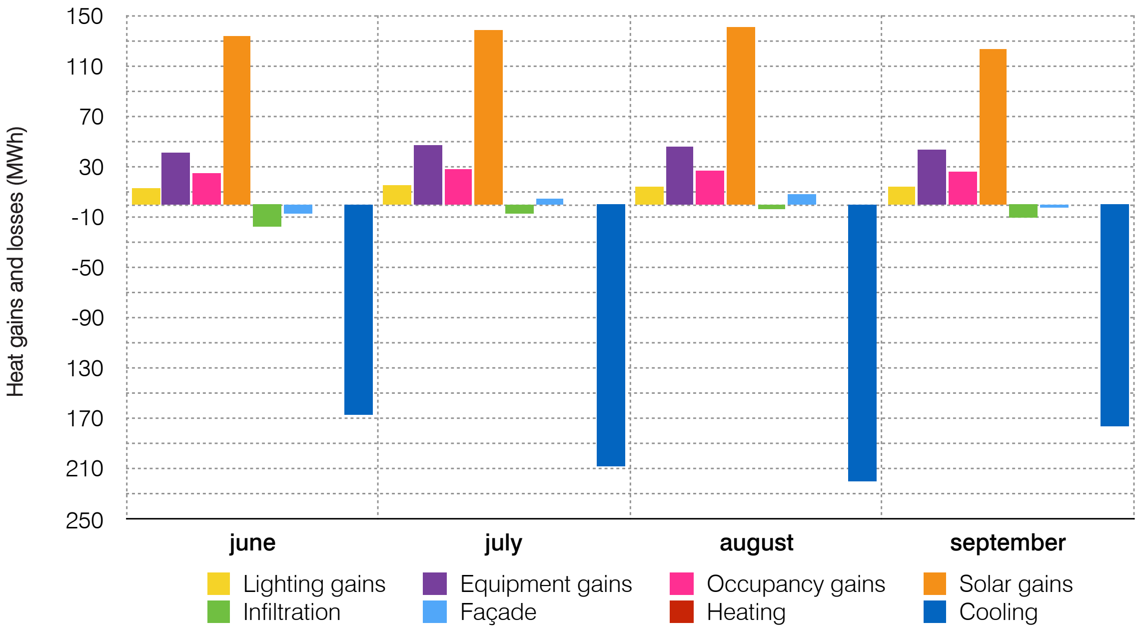


Figure 6.18a - Energy performance of the building on the current state for the typical summer day (July 15th)
Figure 6.18b - Energy performance of the building on the current state for a representative summer week

higher than during the rest of the year, the cooling requirement of the building increases notably compared to winter period. In particular, the peak in terms of energy requirements for cooling is in August (219.12 MWh), when also the solar gain is at its peak (140.51 MWh). For example, the cooling requirement in August is five times bigger compared to that evaluated for December (37.33 MWh), whereas the solar gain is less than doubled from its value in December (64.58 MWh). The other sources of heat gain inside the building, compared to the winter period, become less relevant in relation to the global cooling requirement of the building, but they still are responsible of approximately 80-90 MWh each month.

The external infiltration, overall, does not represent a source of cooling as relevant as in winter: for example, in August, it amounts to 3.29 MWh of cooling energy that corresponds approximately to 1.5% of the energy required to mechanically cool-off the building. This is due to the high operating temperatures that in August are in general higher than 26 °C during the main part of the day and can even go above 30 °C. Globally, over the four-month period, the cooling energy provided through air infiltration contributes in the measure of 5% to the building summer cooling, bearing witness to the potential in terms of energy saving of a correctly scheduled natural ventilation also in summer.



	june	july	august	september	TOTAL
Lighting gain (MWh)	12.95	14.90	14.25	13.60	55.70
Equipment gain (MWh)	41.32	47.52	45.45	43.39	177.68
Occupancy gain (MWh)	24.65	28.35	27.11	25.88	105.99
Solar gain (MWh)	134.31	138.4	140.51	123.82	537.04
External Infiltration (MWh)	-17.67	-6.98	-3.29	-10.77	-38.71
Façade (MWh)	-7.55	4.70	8.74	-1.89	4.00
Heating Requirement (MWh)	0	0	0	0	0
Cooling Requirement (MWh)	-166.77	-208.48	-219.12	-176.68	-771.05

Figure 6.19 - Overall monthly amount of heat gains and losses (Current State)

6.4.3.3. Overview of the results of the building at current state

The overall results referred to the 4-month summer and winter periods show that, in both cases, the requirement for cooling is higher than that for heating (that is equal to 0, in summer), due especially to the transmitted solar gains. It should also be underlined that also the internal gains related to occupancy, equipment and lighting systems have a significant role. However, differently than the solar gains, these can not be eliminated nor easily reduced, because they are essentially linked to the activities that in the building, with its specific function, are performed. The solar gain through the building envelope is the main responsible of the cooling need for this building: in particular, it amounts to 335.83 MWh in winter period (corresponding to 50% of the total heat gains) and to 537.04 MWh, in summer period (corresponding to 61% of the total heat gains). Differently from the other types of heat gain, it can be notably reduced by intervening on the thermal and, especially, solar gain performance of the building envelope.

At current state, in particular, approximately 60% of the solar radiation that strikes the façades of the building is let in as heat (i.e. the g-value of the curtain wall glazing is 58.5%). Improving this aspect could significantly optimize the overall performance of the building and reduce its cooling needs during the year. In addition, especially during winter simulation period, the cooling that could derive from natural ventilation or air infiltration, could be of great relevance to reduce the cooling requirements of the building.

It is not possible, in this phase, and it is not the purpose of this work to make any direct comparison with the actual consumption of the building (which have been provided by the building owner): however, it should be noted, that the relation between simulated summer and winter consumption is the same as the relation occurring through the same periods in real building electricity bills. An approximately 30% higher consumption is calculated by using the simulation software to study building at current state both in summer and winter.

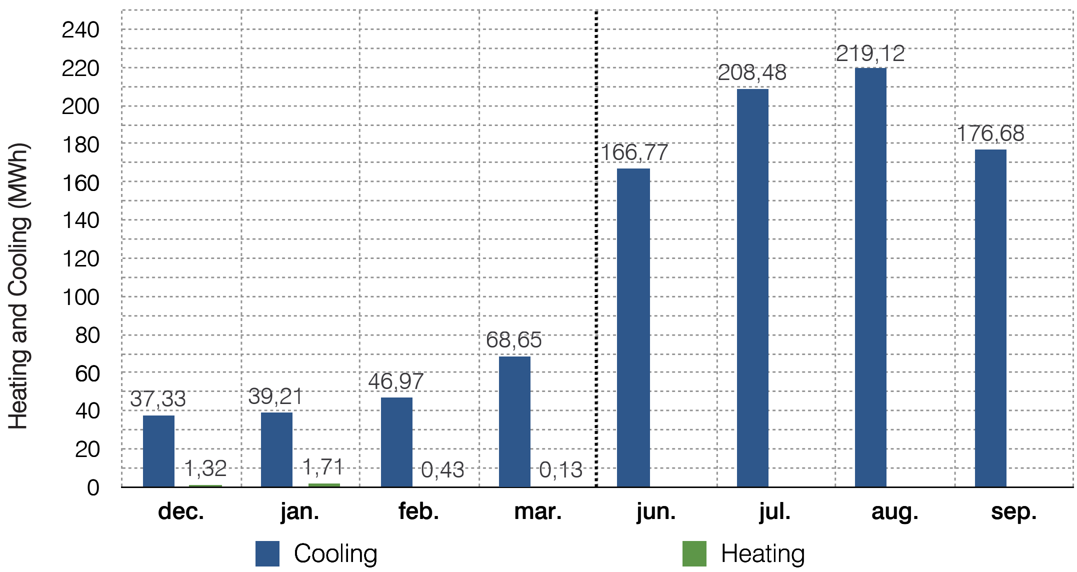


Figure 6.20 - Overall Heating and Cooling Energy required per month, accounting for both the 4-month winter and summer periods

6.5. Simulations of the Retrofitted Building with the new BIPV Envelope

Starting from the results obtained in the simulations of the building at current state, the same analyses have been carried out on the same building with a new envelope made of DSC-integrated glass block panels.

In this case, the Cooling and Heating design calculations have been also useful to make some preliminary assumptions on the best glass block configuration to be used in order to maximize the deriving energy performance of the building.

6.5.1. The new BIPV Envelope

The components considered for retrofitting the building envelope consist of precast, dry-assembled and pre-stressed panels made of glass block integrated with 3rd-generation Dye-sensitized Solar Cell (DSC) module, as widely described in Chapter 4.

The DSC-integrated glass blocks are arranged into components of 1.02m of width and 2.70m of height, each made of 24 elements, laid down in 8 rows and 3 columns, in order to cover the interfloor distance.

A specific element for the mechanical connection of the panels to the load-bearing structure of the building, made of reinforced concrete, has been designed, along with all other subcomponents needed to guarantee an optimal performance according to all essential building requirements (such as, for example, safety, comfort, environmental safeguard, management, appearance).

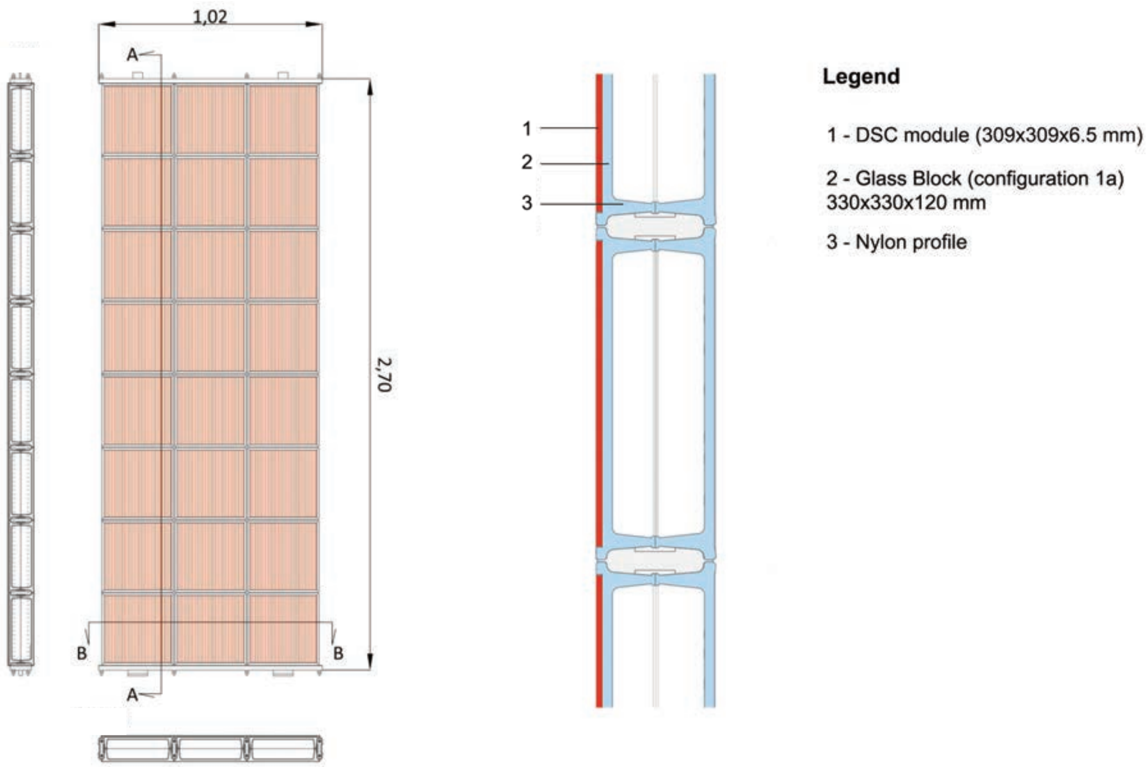


Figure 6.21 - *(left)* View and sections of the glass block panel and *(right)* detailed section depicting its basic subcomponents (DSC module, glass shells, plastic profiles)

The analyses, which have been discussed in Chapter 5, showed the possibility to adopt this technical solution for the construction of translucent façades and roofs able to produce clean energy while reducing the overall building energy consumption, due to the performance provided in terms of thermal insulation and solar protection.

In this study, all four façades of the building were reconfigured and replaced with the DSC-integrated glass block panels in order to maximize the exploitation of the external surfaces for energy harvesting. However, each office was provided with one openable window with low-emissive double-glazing, in order to allow for natural ventilation as well as to guarantee a certain amount of unobstructed clear surface for daylight penetration. Overall, approximately 75% of building skin is cladded in DSC-integrated glass block panels, whereas the remaining 25% is characterized by double-glazing openings, as it can be seen in the comparison illustrated in Figure 6.22.

Figure 6.22 - Picture of the building at current state and rendered view of the reconfigured building envelope configuration (Tutone, 2015; Milia, 2015)

The glass blocks, used in the design of the new building skin, are 330x330x120 mm in dimensions and they are composed of two glass shells (with 10-mm thick face) and a 100-mm thick internal cavity filled with dry air. For the present analyses, among the four "Hypotheses" of DSC integration into the glass block, the chosen one is Configuration 1a, where a dye-sensitized solar module is placed on the external surface of the sun-exposed glass shell and is framed by a peripheral glazed border. The position of the module outside the glass block guarantees highest energy yield, 87% coverage of glass block surface by the DSC module and lower operating temperatures; at the same time, the presence of the glazed border helps the mechanical fixing of the DSC module to the glass shell.

The thermal and optical properties of the product were calculated with the support of WINDOW and Comsol Multiphysics® software, by using the methodology described in chapter 5 and by following the standards UNI EN 673:2011 and UNI EN 410:2011. The main properties of this product, as required by the Design Builder, are reported in Table 6.4.

The global thermal and optical performance parameters of the glazing system as calculated by WINDOW and Comsol Multiphysics, are the following: U value: 2.6 W/m^{2}K; g-value: 39.0%; Tvis: 0.272. The U value of the frame (i.e. nylon plastic profiles), which was assessed

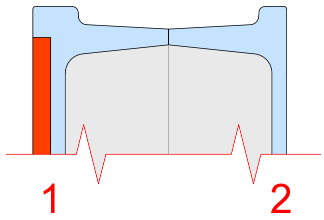
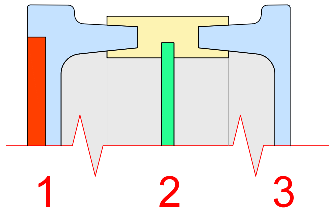
					
	Configuration 1a		Configuration 1b		
	1) DSC/glass	2) Glass shell	1) DSC/glass	2) LowE glass	3) Glass shell
Thickness (mm)	16.5	10.0	16.5	4.000	10.0
Thermal conductivity (W/mK)	1.000	1.000	1.000	1.000	1.000
Solar Transmittance	0.375	0.747	0.375	0.250	0.747
Solar Reflectance, front	0.094	0.070	0.094	0.593	0.070
Solar Reflectance, back	0.094	0.070	0.094	0.474	0.070
Visible Transmittance	0.312	0.878	0.312	0.676	0.878
Visible Reflectance, front	0.078	0.080	0.078	0.099	0.080
Visible Reflectance, back	0.078	0.080	0.078	0.105	0.080
Infrared Transmittance	0.000	0.000	0.000	0.000	0.000
Front emissivity	0.837	0.837	0.837	0.013	0.837
Back emissivity	0.837	0.837	0.837	0.837	0.837

Table 6.4 - Properties of the glass layers composing the DSC-integrated Glass Block, according to Configuration 1a and 1b, as required by DesignBuilder

by means of COMSOL Multiphysics, is equal to 2.9 W/m^{2}K. The U value of this glass block configuration is higher than that of the glazing of the current state. In this first study, it has been decided to start with the evaluation of the "basic" product configuration and analyze its benefits at a first stage. Indeed, the U values of both glass block and its framing are below the transmittance limits, imposed by the Legislative Decree 311/2006 for the area of Palermo[12]. In this specific case, indeed, the simulations on the current state demonstrated that it is not necessary to improve significantly the thermal insulation of the building envelope, compared to the existing solution[13]. Indeed, due to the climatic location of the city of Palermo (high solar radiation[14] and mild winter temperatures[15]) as well as to the internal heat gains from the office equipment, the results even underlined the necessity of some cooling during wintertime. On the other hand, the solar gain reduction provided by the PV-integrated glass blocks is fundamental for the optimization of the energy performance of the building envelope in summer; in Configuration 1a, de facto, there is an approximately 20-point difference in terms of solar gain coefficient compared to the current state envelope: de facto, g-value is 39%, whereas in current state glazing g-value is 58.5%. This might compensate for the lower thermal transmittance and lead to an improved summer performance.

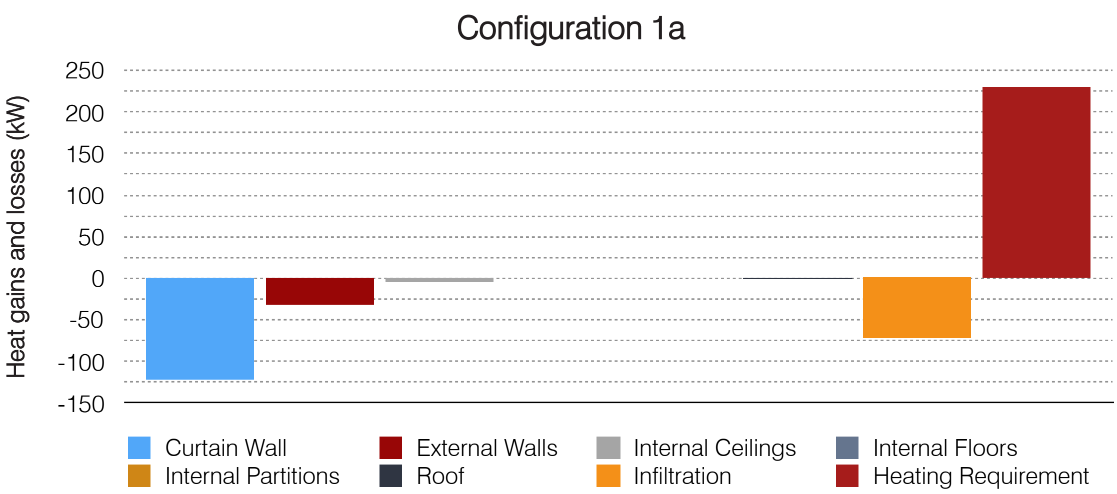
Subsequently, another configuration has been studied (from now on referred to as Configuration 1b): it consists of a glass block where the DSC module is integrated on the external surface of the sun-exposed glass shell and is framed by a peripheral glazed border — just as in the Configuration 1a — but also where a low-emissive glass sheet (whose detailed properties are also shown in Table 6.4) is inserted inside the cavity that is subsequently subdivided by it into two chambers. The global thermal and optical performance parameters of Configuration 1b, also calculated by means of WINDOW and Comsol Multiphysics, are the following: U value: 1.2 W/m^{2}K; g-value: 16.1%; Tvis: 0.189. Here, both the thermal insulation (U value) as well as the solar protection performance vary from the current state: the g-value, in particular, is significantly reduced (of over 40 points), reaching 16.1% thanks to the insertion inside the cavity of the glass block of a low-emission glass sheet. The U value of the frame (2.9 W/m^{2}K) remains unvaried in both cases.

6.5.2. Heating Design calculation

The heating design calculations of the reconfigured building with the new BIPV envelope made of DSC-integrated 33x33 glass blocks according to *Configuration 1a* show, as expected, a poorer winter performance of the new envelope. Indeed, the lower U value of the DSC-integrated glass blocks in Configuration 1a generates an increase in the heat losses occurring through the building envelope (-121.39 kW) and, thus, of the total heating capacity required (229 kW). Results are reported in Figure 6.23 and in Table 6.5.

The total heating design capacity of the reconfigured building is equal to 412.37 kW that is 18% higher than that measured at current state. This is mainly due, as it is possible to see from Figure 6.23, to the heat losses linked to the new envelope that has a smaller thermal resistance compared to the building at current state. De facto, the heat losses related to the envelope solution goes from 85.48 kW (at current state) to 121.39 kW (in the reconfigured building), whereas all other parameters remain basically unvaried. This might represent a problem (in abstract, as regard e.g. the initial costs of the HVAC system and winter performance), however a complete simulation could be useful to figure out the actual performance over longer periods, given the warm climate area where the building is located.

If we consider *Configuration 1b*, which has a lower U value than the glazing at current state and than Configuration 1a, the results of winter design calculation change significantly as shown in Figure 6.24. As expected, the main change is that related to the heat loss occurring through the building envelope: de facto, with the new envelope according to Configuration 1b, the heat loss is almost halved compared to the glass block Configuration 1a going from 121.39 kW to 69.37 kW. This results into a significant drop in the heating requirement of the building compared to the results obtained with Configuration 1a. Even if smaller, a certain decrease in the heating requirement can be noted also compared to current state. The total design capacity of the heating system is thus reduced to 319.80 kW, that means a drop of 23% compared to Configuration 1a (412.37 kW) and of 8% compared to current state (348.45 kW).

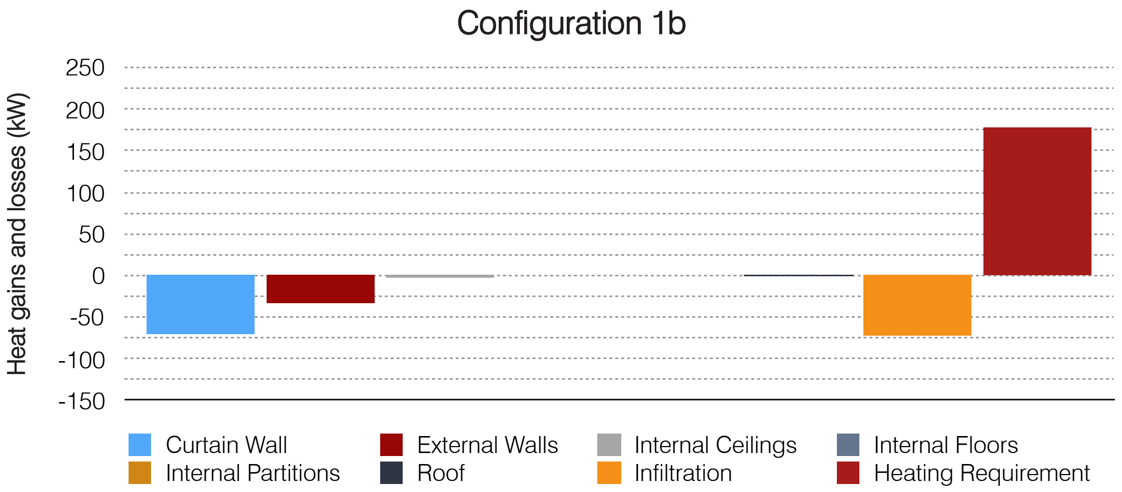


Curtain Wall	-121.39
External Walls	-31.96
Internal Ceilings	-3.85
Internal Floors	0
Internal Partitions	0.92
Roof	-1.69
Infiltration	-71.19
Heating Requirement	229.10

Figure 6.23 - Heat gains (>0) and losses (>0)

Level	Zone	Operating temp. (°C)	Heat loss (kW)	Heating Capacity (kW)
Floors 1-9	Offices West corner	18.23	9.02	16.24
	Offices South corner	18.17	7.50	13.50
	Offices SE (group 3)	18.74	10.12	18.22
	Corredor	19.33	16.9	30.43
	Toilets (west)	18.47	7.33	13.19
	Offices SE (group 2)	18.98	24.88	44.78
	Toilets (east)	18.48	7.25	13.05
	Offices SE (group 1)	18.75	10.08	18.15
	Offices East corner	18.27	8.37	15.07
	Offices NW	18.98	66.35	119.43
	Offices North corner	18.16	7.16	12.90
10th Floor	Offices West corner	18.09	1.09	1.96
	Offices South corner	18.03	0.91	1.63
	Offices SE (group 3)	18.66	1.20	2.17
	Corredor	19.26	2.05	3.68
	Offices SE (group 2)	18.90	2.97	5.34
	Offices SE (group 1)	18.67	1.19	2.14
	Offices East corner	17.88	1.17	2.11
	Offices NW	18.90	7.92	14.26
	Offices North corner	18.00	0.87	1.57
Ground Floor	Control Room A	19.25	1.11	2.00
	Entrance	18.64	25.32	45.58
	Meeting Zone	18.55	1.21	2.17
	Toilets (east)	19.19	0.49	0.89
	Control Room B	19.21	1.13	2.04
	Toilets (west)	18.39	0.98	1.76
	Bar	18.20	4.51	8.11
	Total		229.10	412.37

Table 6.5 - Summary of the heating design calculation including the resulting heating design capacity of the system



Curtain Wall	-69.37
External Walls	-32.44
Internal Ceilings	-2.42
Internal Floors	-0.51
Internal Partitions	0
Roof	-1.74
Infiltration	-71.24
Heating Requirement	177.66

Figure 6.24 - Heat gains (>0) and losses (>0)

Level	Zone	Operating temp. (°C)	Heat loss (kW)	Heating Capacity (kW)
Floors 1-9	Offices West corner	18.90	5.69	10.24
	Offices South corner	18.84	4.76	8.56
	Offices SE (group 3)	19.06	7.76	13.96
	Corredor	19.42	15.34	27.60
	Toilets (west)	18.51	7.14	12.85
	Offices SE (group 2)	19.33	17.63	31.73
	Toilets (east)	18.53	7.06	12.71
	Offices SE (group 1)	19.07	7.66	13.80
	Offices East corner	18.84	5.63	10.13
	Offices NW	19.36	45.58	82.04
	Offices North corner	18.85	4.46	8.02
10th Floor	Offices West corner	18.74	0.72	1.30
	Offices South corner	18.68	0.61	1.09
	Offices SE (group 3)	18.96	0.95	1.71
	Corredor	19.33	1.89	3.40
	Offices SE (group 2)	19.24	2.16	3.89
	Offices SE (group 1)	18.99	0.93	1.67
	Offices East corner	18.38	0.89	1.60
	Offices NW	19.25	5.74	10.33
	Offices North corner	18.66	0.58	1.05
Ground Floor	Control Room A	19.27	1.09	1.97
	Entrance	18.65	25.19	45.34
	Meeting Zone	18.57	1.19	2.15
	Toilets (east)	19.20	0.49	0.88
	Control Room B	19.23	1.12	2.01
	Toilets (west)	18.40	0.97	1.75
	Bar	18.22	4.46	8.02
	Total		177.69	319.80

Table 6.6 - Summary of the heating design calculation including the resulting heating design capacity of the system

6.5.3. Cooling Design calculation

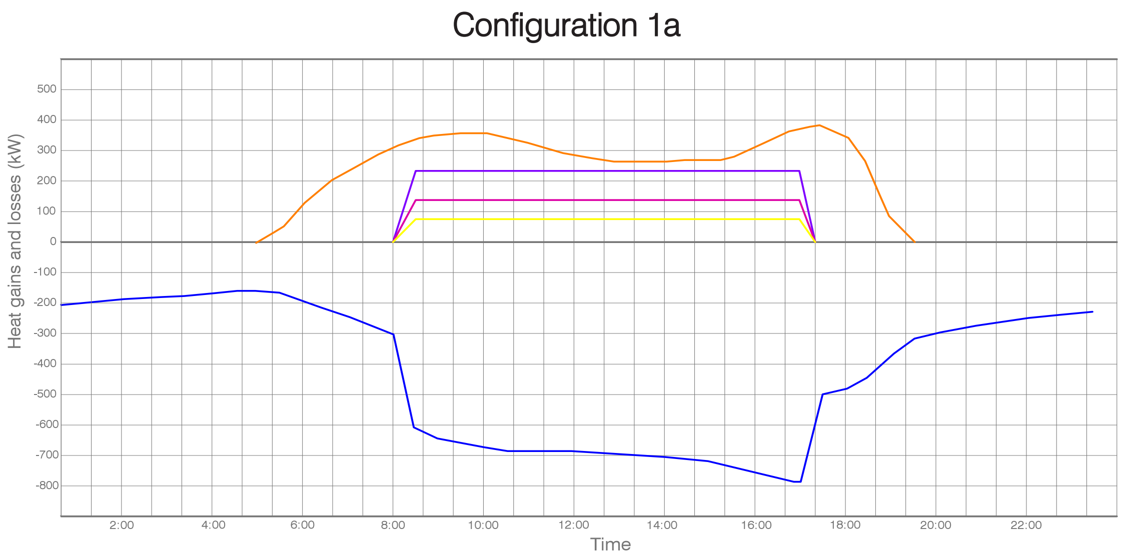
The Cooling Design calculations on the reconfigured building, as already underlined, take into account the energy performance of the building during a typical summer day. Both Configurations 1a and 1b have been analysed. Below (Table 6.7) are reported the main performance parameters of the glazing of these envelope solutions as well as the current state curtain wall. As it is clear from the data in the table the lowest U and g values are those of Configuration 1b, which is also expected to be the best performing of the three.

	Current state glazing	Configuration 1a	Configuration 1b
U value (W/m^2K)	1.9	2.6	1.2
g-value	58.5%	39.0%	16.1%
Visible transmittance	0.761	0.272	0.189

Table 6.7 - Comparison of the three glazing systems analyzed

Despite the lower thermal insulation performance compared to the curtain wall at current state, *Configuration 1a* should be useful to reduce the solar gain across the envelope, thanks to the slight "sun-shading effect" provided by the new BIPV envelope (and, in particular, due to the DSC module integrated into the glass blocks). De facto, by looking at the graph provided in Figure 6.25, for example, the solar gain through the building envelope reaches a peak between 5:00 and 6:00 pm with a power close to 400 kW, whereas at current state this value, in the same day of the year (i.e. July 15^{th}), amounts to 505 kW (as shown in Figure 6.15). Nevertheless, as it is possible to note in Table 6.8, where the peak cooling (877.64 kW) and the cooling design capacity (1140.93 kW) are reported, only a very small decrease in cooling requirements, compared to current state, is registered for the building with the new BIPV envelope made of DSC-integrated glass blocks according to Configuration 1a. This should be probably due to the higher thermal transmittance of the new building envelope. Indeed, the thermal insulation performance of the new envelope is less effective than that of the curtain wall that clads the building at current state and this, despite the solar protection provided by the new building envelope, might result into higher costs for maintaining the indoor temperatures to the design levels, also given the high outdoor temperatures, steadily above the 26°C comfort temperature.

As regards the *Configuration 1b* (whose results are reported in Figure 6.26 and Table 6.9), the new building envelope is not only more insulating, but also provides a solar factor that is significantly lower than that of the double-glazing of the curtain wall at current state. Thus, the solar heat gain through the building envelope goes down significantly compared to both current state and Configuration 1a, whereas all other heat gains remain unvaried. This, combined with the improved thermal insulation performance, allows for a further improvement of building cooling requirements that reach 738.92 kW and, subsequently to a 22% reduction of design capacity (960.60 kW) of the cooling system of the building compared to current state calculation.

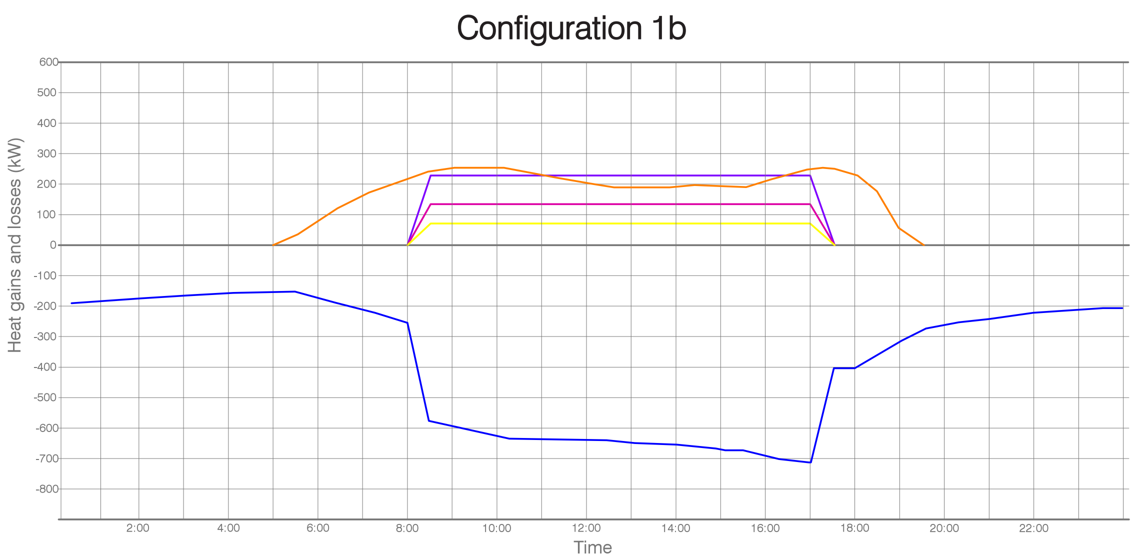


	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Lighting gain (kW)	0.00	0.00	0.00	0.00	71.97	71.97	71.97	71.97	0.00	0.00	0.00
Equipment gain (kW)	0.00	0.00	0.00	0.00	229.6	229.6	229.6	229.6	0.00	0.00	0.00
Occupancy gain (kW)	0.00	0.00	0.00	0.00	136.9	136.9	136.9	136.9	0.00	0.00	0.00
Solar gain (kW)	0.00	0.00	121.2	305.5	351.46	285.8	262.6	306.9	348.8	0.00	0.00
Cooling Requirement (kW)	-213.2	-191.7	-217.1	-325.5	-698.2	-713.5	-725.4	-776.6	-504.6	-323.8	-275.7

Figure 6.25 - Cooling design calculation: heat gain (>0) and losses due to cooling (<0) on typical summer day July, 15th

Level	Zone	Peak cooling time	Max operating temp (°C)	Peak cooling (kW)	Design capacity (kW)
Floors 1-9	Offices West corner	17:00	32.2	45.03	58.54
	Offices South corner	16:30	31.7	33.24	43.21
	Offices SE (group 3)	11:30	28.6	29.45	38.29
	Corredor	17:00	27.3	40.61	52.80
	Toilets (west)	16:30	28.0	11.64	15.13
	Offices SE (group 2)	11:30	28.7	179.95	233.93
	Toilets (east)	17:00	28.0	11.74	15.26
	Offices SE (group 1)	11:30	28.6	30.24	39.32
	Offices East corner	09:00	31.7	38.67	50.27
	Offices NW	17:00	28.4	216.67	281.68
	Offices North corner	08:30	31.1	27.57	35.85
10th Floor	Offices West corner	17:00	34.8	7.42	9.64
	Offices South corner	16:30	33.7	5.19	6.75
	Offices SE (group 3)	11:30	29.4	4.28	5.56
	Corredor	17:00	27.5	5.07	6.59
	Offices SE (group 2)	11:30	29.3	12.20	15.86
	Offices SE (group 1)	11:30	29.6	4.46	5.80
	Offices East corner	09:00	34.1	6.40	8.32
	Offices NW	17:00	29.3	33.05	42.97
	Offices North corner	08:30	33.0	4.34	5.65
Ground Floor	Entrance	15:00	28.9	3.77	4.90
	Toilets (west)	17:00	29.8	92.15	119.80
	Bar	09:30	31.7	6.46	8.40
	Meeting Zone	17:00	27.5	1.08	1.41
	Control Room A	17:00	27.6	3.31	4.30
	Toilets (east)	17:00	27.8	1.33	1.73
	Control Room B	17:00	32.0	22.30	28.99
	Total			877.64	1140.93

Table 6.8 - Summary of the cooling design calculation indicating, for each zone, the resulting cooling design capacity of the system, as well as the time of peak cooling and the maximum operating tempeature



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Lighting gain (kW)	0.00	0.00	0.00	0.00	71.97	71.97	71.97	71.97	0.00	0.00	0.00
Equipment gain (kW)	0.00	0.00	0.00	0.00	229.6	229.6	229.6	229.6	0.00	0.00	0.00
Occupancy gain (kW)	0.00	0.00	0.00	0.00	136.9	136.9	136.9	136.9	0.00	0.00	0.00
Solar gain (kW)	0.00	0.00	80.98	205.0	236.2	194.0	180.1	196.0	218.15	0.00	0.00
Cooling Requirement (kW)	-188.8	-172.4	-190.1	-266.7	-620.5	-633.4	-644.4	-679.9	-396.7	-270.6	-235.4

Figure 6.26 - Cooling design calculation: heat gain (>0) and losses due to cooling (<0) on typical summer day July, 15th

Level	Zone	Peak cooling time	Max operating temp (°C)	Peak cooling (kW)	Design capacity (kW)
Floors 1-9	Offices West corner	17:00	30.5	31.91	41.48
	Offices South corner	16:30	30.0	22.94	29.83
	Offices SE (group 3)	11:30	27.9	23.52	30.58
	Corredor	17:00	27.2	38.08	49.50
	Toilets (west)	16:30	27.9	11.34	14.75
	Offices SE (group 2)	12:00	28.1	162.24	210.92
	Toilets (east)	16:30	27.9	11.44	14.88
	Offices SE (group 1)	11:30	28.0	24.08	31.30
	Offices East corner	09:00	30.3	28.67	37.27
	Offices NW	17:00	27.7	171.40	222.82
	Offices North corner	09:00	29.5	18.84	24.50
10th Floor	Offices West corner	17:00	32.5	5.27	6.85
	Offices South corner	16:30	31.6	3.60	4.68
	Offices SE (group 3)	11:30	28.7	3.42	4.44
	Corredor	17:00	27.4	4.79	6.23
	Offices SE (group 2)	11:30	28.5	9.52	12.37
	Offices SE (group 1)	11:30	28.8	3.54	4.60
	Offices East corner	09:00	32.3	4.73	6.15
	Offices NW	17:00	28.6	26.60	34.58
	Offices North corner	09:00	30.9	2.93	3.81
Ground Floor	Entrance	15:00	28.9	3.75	4.87
	Toilets (west)	17:00	29.7	91.96	119.55
	Bar	09:30	31.6	6.44	8.37
	Meeting Zone	17:00	27.5	1.08	1.40
	Control Room A	17:00	27.5	3.29	4.27
	Toilets (east)	17:00	27.8	1.33	1.73
	Control Room B	17:00	32.0	22.21	28.87
	Total			738.92	960.60

Table 6.9 - Summary of the cooling design calculation indicating, for each zone, the resulting cooling design capacity of the system, as well as the time of peak cooling and the maximum operating tempeature

6.5.4. Dynamic simulations (Configuration 1a)

As regards the simulations of the energy performance of the building characterized by the new BIPV glass block skin, a significant decrease can be individuated in terms of solar gains compared to the current state. As a result, a decrease in the energy requirements for cooling, compared to current state, is expected both in winter and summer analyses. The other heat gains associated to people, equipment and lighting are the same as in the current state.

6.5.4.1. Winter analyses (Configuration 1a)

In the typical winter week (Figure 6.27b), the solar gain reduction that is provided by the new envelope produces a decrease in the cooling requirements of the building but, at the same time, the higher U value of the new envelope corresponds to a certain increase in the needs for heating during early morning and night hours of the day. It is important to note, in particular, that during the weekend and at night as well, even if the building is not occupied by its users and the other heat gains related to occupancy, equipment, and lighting systems are absent, its HVAC system is active in order to avoid an excessive cooling-off of the building.

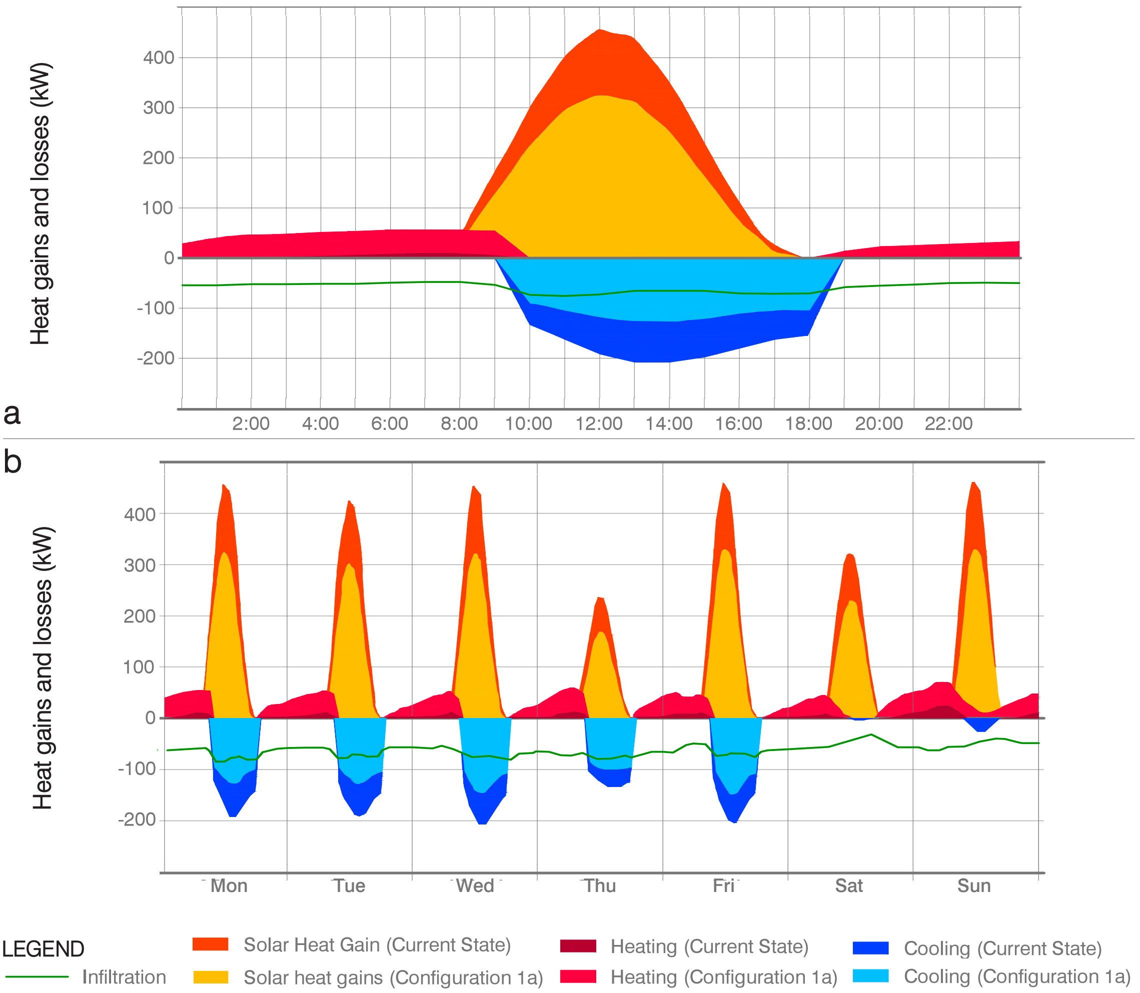
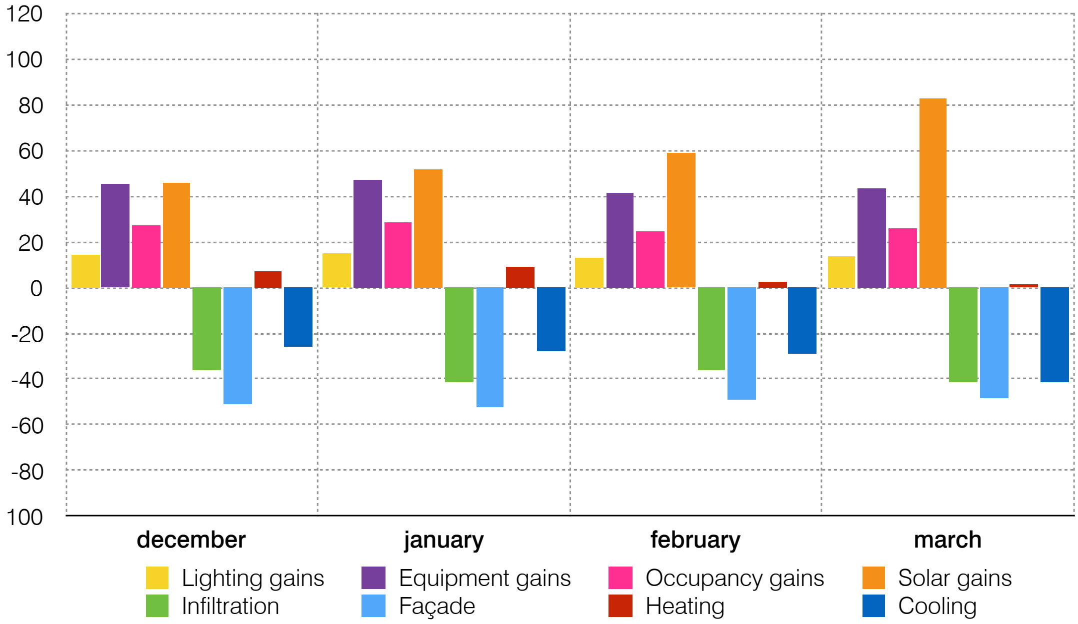


Figure 6.27a - Energy performance of the retrofitted building compared with current state (January 3rd, Conf. 1a)
Figure 6.27b - Energy performance of the retrofitted building compared with current state (January 1-7th, Conf. 1a)

This would indeed lead to a large pre-heating requirement that could not be otherwise sustained in shorter times by the system capacity, in order to get back to the comfort temperatures in the morning, when the building is occupied again by users[16].

The solar heat gain varies significantly over the analysed week. This is of great relevance in determining the cooling and/or heating needs of the building, especially during weekends when solar gain is the only heat source for the building. On Sunday, for example, due to the solar heat gain, there is some need for cooling in the central hours of the day and, as in the rest of the week, some need for heating in the morning and night hours of the day. On Saturday, instead, the solar heat gain stands close to or below 200 kW during the whole day, so, in order to avoid an excessive cooling-off of the building, some heating is required, whereas there is no need for any cooling in the reconfigured building (but this is not true for the building at current state).

This behaviour is reflected also in the 4-month winter simulation (Figure 6.28), where it is possible to underline about 100 MWh (29%) decrease of solar heat gain through the building envelope, resulting into a 68.56 MWh drop in cooling requirements of the building. On the other hand, a certain increase (approximately 20 MWh) in global heating requirement can be noted as well.



	december	january	february	march	TOTAL
Lighting gain (MWh)	14.25	14.90	12.95	13.60	55.70
Equipment gain (MWh)	45.45	47.52	41.32	43.39	177.68
Occupancy gain (MWh)	27.11	28.35	24.65	25.88	105.98
Solar gain (MWh)	45.99	51.55	58.86	82.78	239.18
External Infiltration (MWh)	-36.33	-41.31	-36.47	-41.62	-155.73
Façade (MWh)	-50.91	-52.33	-49.36	-48.36	-200.96
Heating Requirement (MWh)	7.26	9.10	2.82	1.13	20.31
Cooling Requirement (MWh)	-25.89	-27.53	-28.92	-41.26	-123.60

Figure 6.28 - Overall monthly amount of heat gains and losses (Configuration 1a)

6.5.4.2. Summer analyses (Configuration 1a)

Analysing a typical summer day, the reduction in terms of solar gains, provided by the new building skin, results in a corresponding decrease of cooling loads compared to the building at current state (Figure 6.29a).

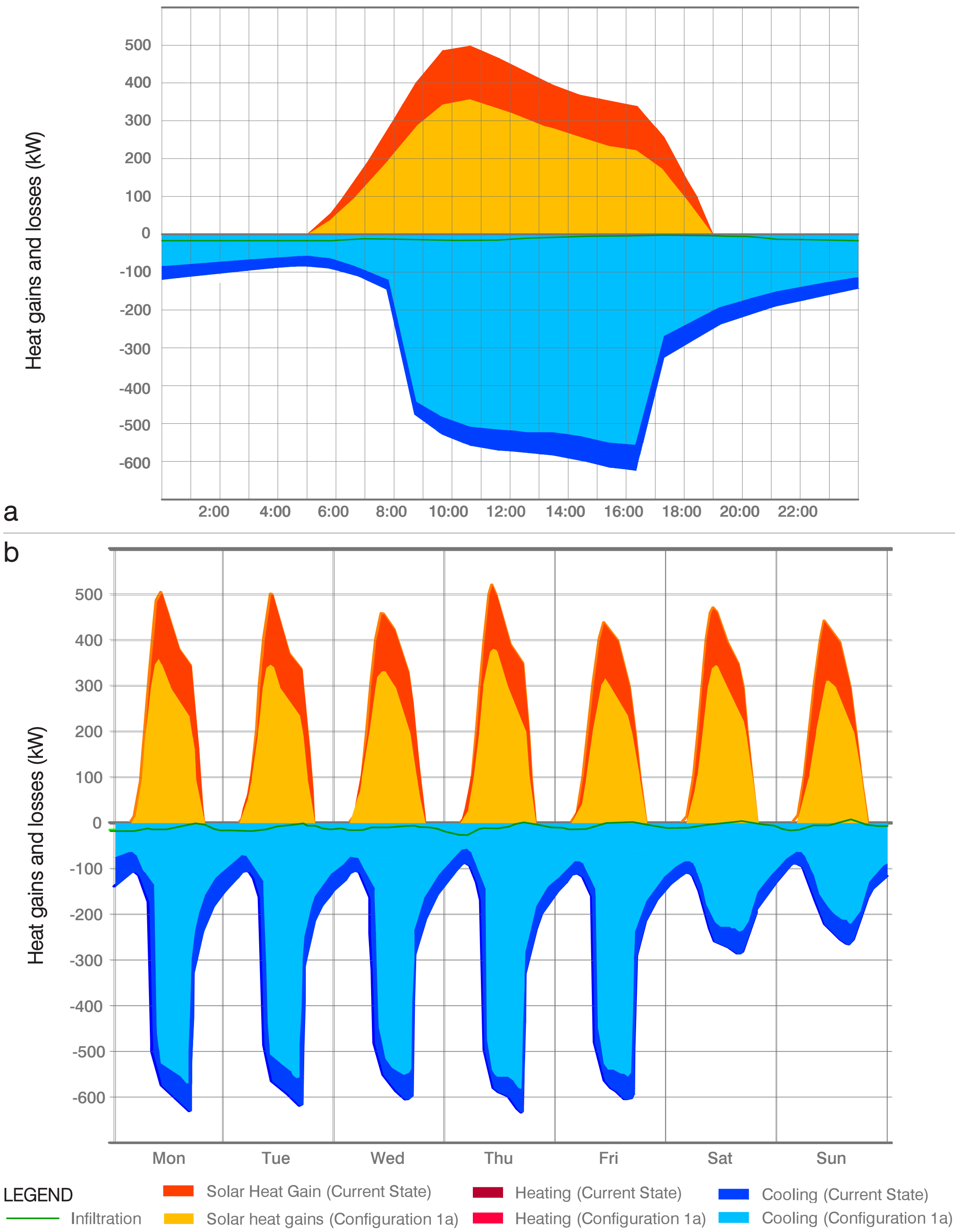
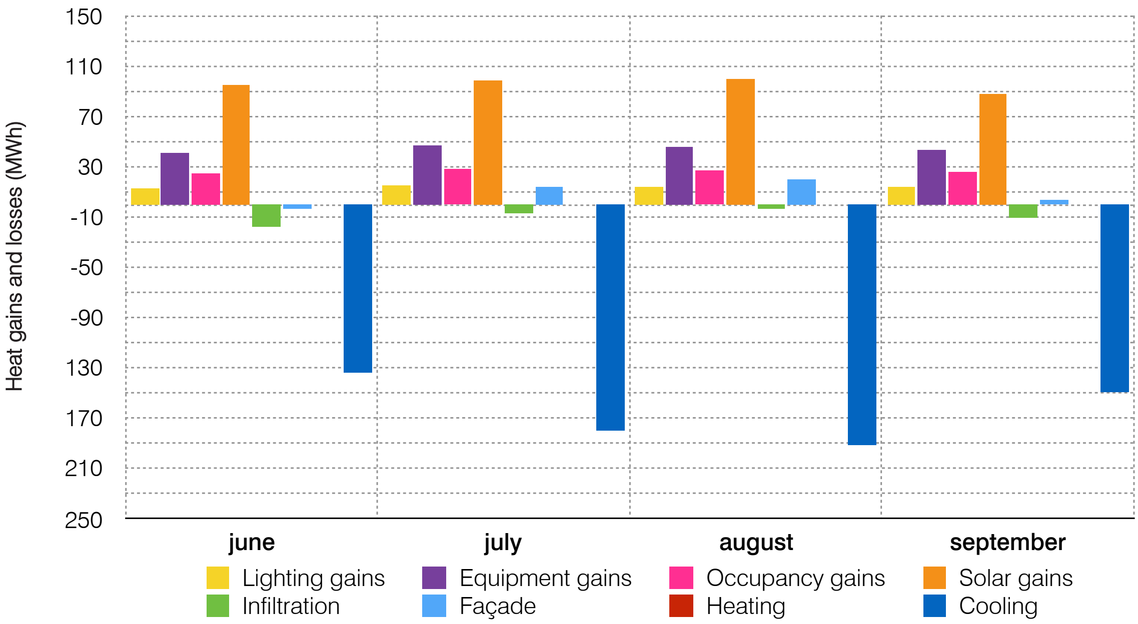


Figure 6.29a - Energy performance of the retrofitted building compared with current state (July 15th, Conf. 1a)
Figure 6.29b - Energy performance of the retrofitted building compared with current state (July 8-14th, Conf. 1a)

The same behaviour can be evidenced also by looking at the results of the analyses of the typical summer week (Figure 6.29b). It is of relevance to note that it is not possible to find a direct correlation between the peak in terms of solar heat gain and the peak in cooling. Indeed, regardless of the solar gain variations through the day (generally occurring at approximately 10:00 am in the morning) and through the week, the peak in cooling always occurs in the afternoon (around 5:00 pm). This is probably due to the heat accumulation occurring throughout the working hours of the day and deriving from solar radiation, occupancy, equipment, and so on. From Figure 6.29, it is also evident how small is the cooling effect related to the external air infiltration: it might even generate negative heating effects, based on the environmental conditions, turning into a heat source in some moments of the week (e.g. Sunday afternoon).

As regards the 4-month summer period from June to September (Figure 6.30), the solar gain through the envelope goes down of about 150 MWh compared with current state. To this 29% drop in solar gain corresponds a decrease of around 117 MWh in terms of cooling requirements of the building. Therefore, a 18% reduction of the summer cooling of the building can be evaluated. This discrepancy between the reduction of solar heat gain and the cooling requirements might be linked to the U value of the new building envelope that is less insulating compared to the current state curtain wall.



	june	july	august	september	TOTAL
Lighting gain (MWh)	12.95	14.90	14.25	13.60	55.70
Equipment gain (MWh)	41.32	47.52	45.45	43.39	177.68
Occupancy gain (MWh)	24.65	28.35	27.11	25.88	105.99
Solar gain (MWh)	95.83	98.86	100.4	88.38	383.47
External Infiltration (MWh)	-17.6	-6.94	-3.25	-10.68	-38.47
Façade (MWh)	-3.38	13.70	19.53	3.61	33.46
Heating Requirement (MWh)	0	0	0	0	0
Cooling Requirement (MWh)	-134.27	-179.64	-191.58	-148.75	-654.24

Figure 6.30 - Overall monthly amount of heat gains and losses (Configuration 1a)

This might imply some additional cooling, for the maintenance of indoor comfort temperatures when outside is warmer than inside. However, it is clear how reducing the effect of the main responsible for heat gain (i.e. the solar heat crossing the building envelope) is already an effective strategy, that cuts down a relevant portion of the consumption of the building.

6.5.5. Dynamic simulations (Configuration 1b)

The dynamic simulations are now executed also by taking into account the Configuration 1b. The heating and cooling design calculations have already been conducted and the aim of the simulations reported here is to evaluate the actual benefits on a long-term basis of this solution, reducing both U and g values compared to the two already studied.

6.5.5.1. Winter analyses (Configuration 1b)

The results of the typical winter day and week, compared to those of current state analyses, are reported in Figure 6.31. From the results, it is evident that there is an even more significant drop in the solar heat gain compared to current state, due to the addition to Configuration 1a of the low-emissive glass sheet. However, this does not correspond to an

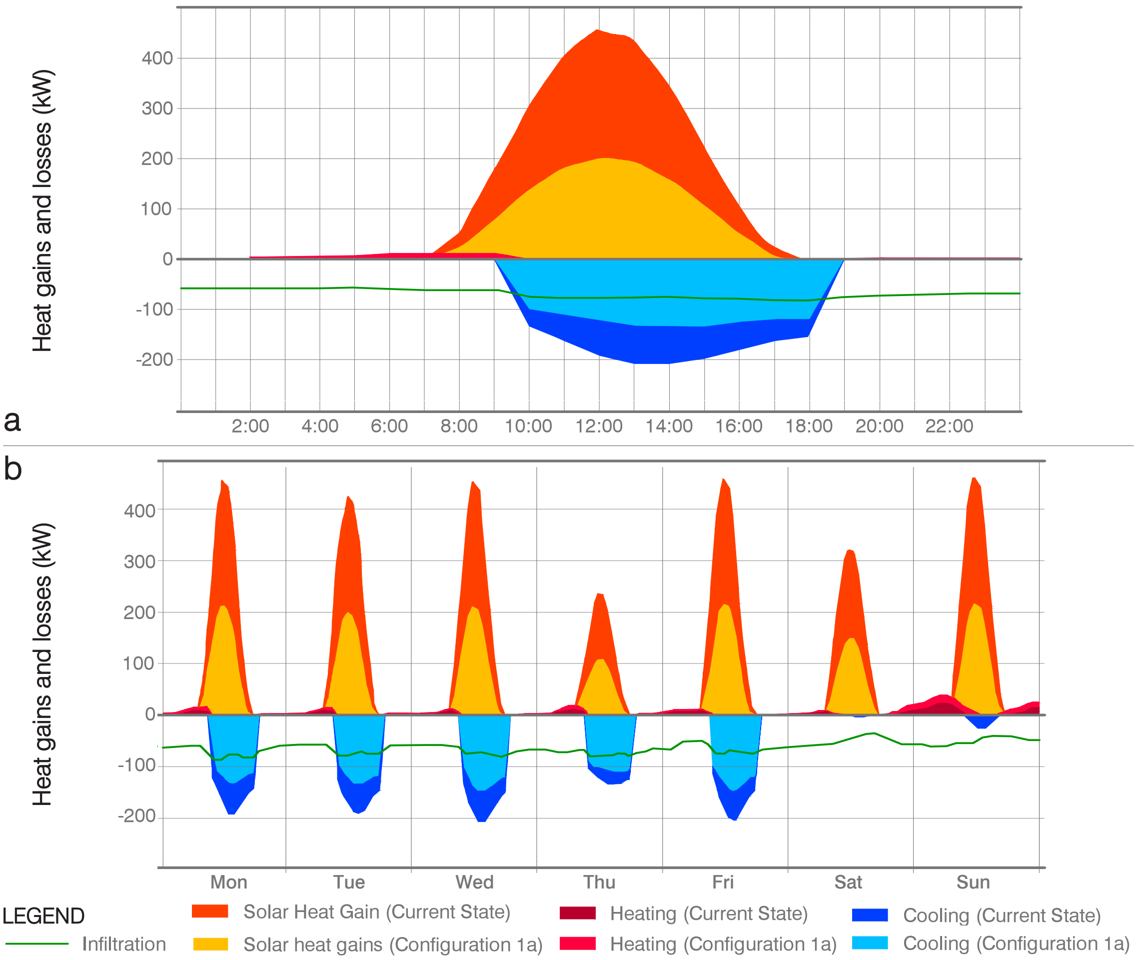
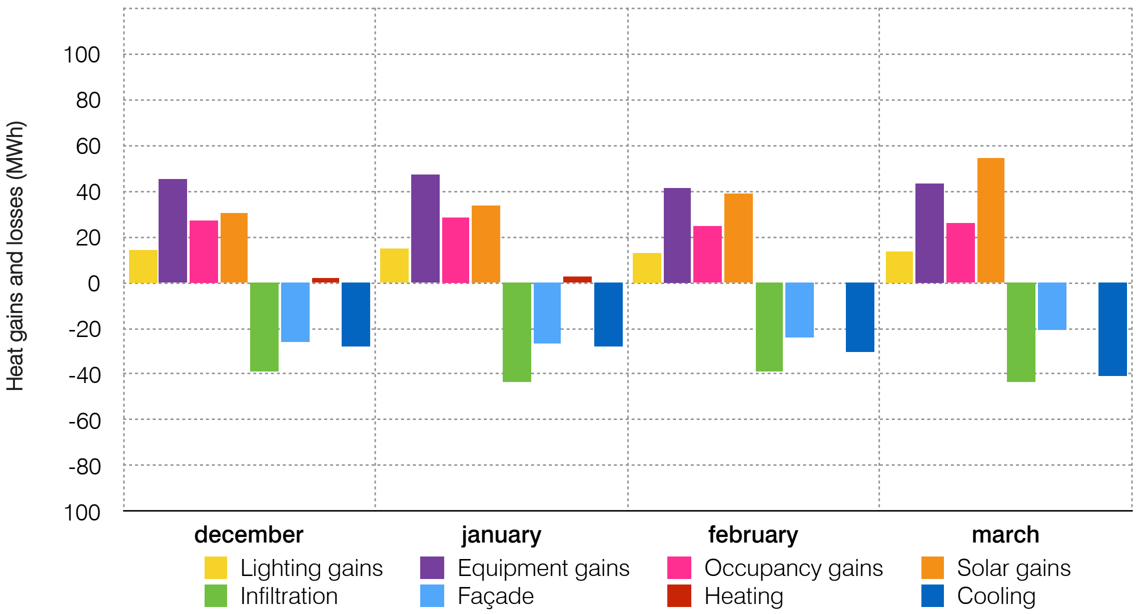


Figure 6.31a - Energy performance of the retrofitted building compared with current state (January 3rd, Conf. 1b)
Figure 6.31b - Energy performance of the retrofitted building compared with current state (January 1-7th, Conf. 1b)

equally reduced cooling requirement (see Figure 6.27a). Actually, the peaks in the cooling need of Configurations 1a and 1b – both notably lower than current state results – are actually quite close. This could be due to the higher thermal insulation of Configuration 1b, an aspect that, in this specific case where the main problem, also in winter, is the cooling of the building, represents a downside. Indeed, one should think to the fact that a more insulating envelope might complicate the process of exhaustion of building's overheating generated by internal and solar heat gains, when outside the temperature is lower, as in this case. In parallel, the heating requirement goes down significantly compared to Configuration 1a and it results very close to that of the current state, even if slightly higher[17].

Overall, the solar gain, calculated over the whole winter period, goes down from 335 MWh of the current state to 157 MWh, meaning that less than half solar energy is let in through the envelope. However, only an 18% reduction in cooling load is registered. Most importantly, the winter cooling requirement compared to Configuration 1a is also slightly higher (of 3 MWh) probably due to the above-discussed downside related, in this case, to a higher thermal insulation. The heating, on the other hand, is 4 times lower than Configuration 1a and only slightly higher than current state, so that overall Configuration 1b turns out the least demanding in terms of global cooling and heating needs among the tested solutions (Figure 6.32).

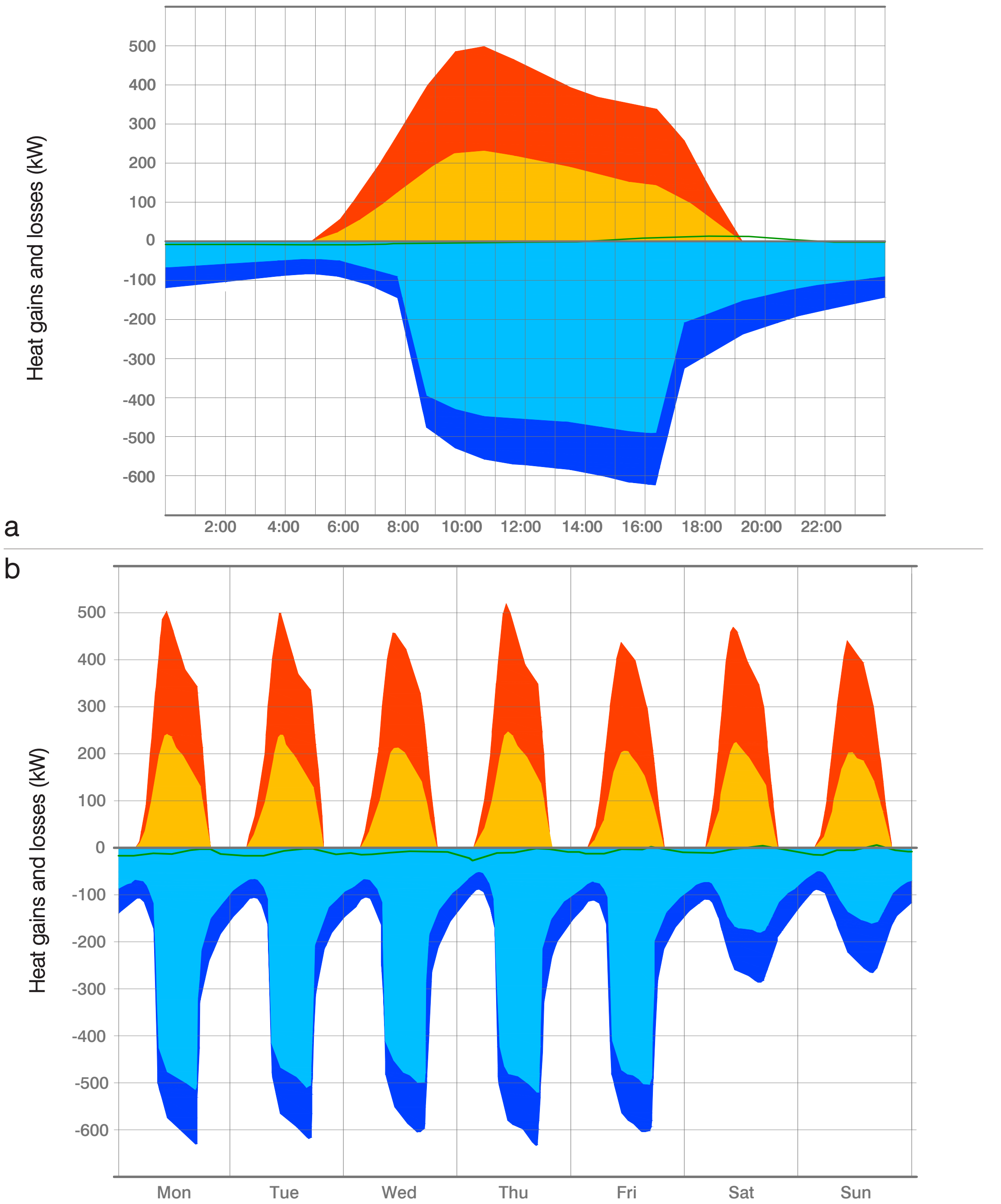


	december	january	february	march	TOTAL
Lighting gain (MWh)	14.25	14.90	12.95	13.6	55.7
Equipment gain (MWh)	45.45	47.52	41.32	43.38	177.67
Occupancy gain (MWh)	27.11	28.34	24.65	25.88	105.98
Solar gain (MWh)	30.11	33.76	38.65	54.57	157.09
External Infiltration (MWh)	-38.6	-43,00	-38.5	-43.5	-163.6
Façade (MWh)	-26.09	-26.55	-23.57	-20.86	-97.07
Heating Requirement (MWh)	1.76	2.61	0.60	0.20	5.17
Cooling Requirement (MWh)	-27.77	-27.92	-30.39	-40.83	-126.91

Figure 6.32 - Overall monthly amount of heat gains and losses (Configuration 1b)

6.5.5.2. Summer analyses (Configuration 1b)

In summer analyses the benefits related to the higher thermal insulation and the lower solar heat gain of the Configuration 1b become more evident than in winter. Results in the typical summer day and week are compared to current state results in Figure 6.33.



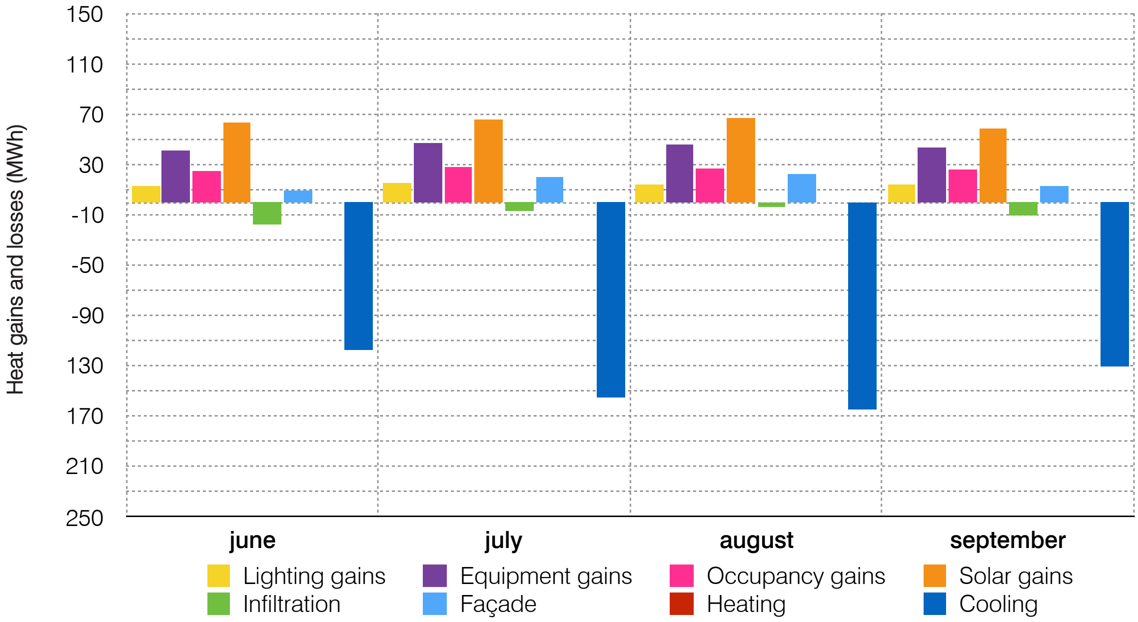
LEGEND
Infiltration
Solar Heat Gain (Current State)
Solar heat gains (Configuration 1a)
Heating (Current State)
Heating (Configuration 1a)
Cooling (Current State)
Cooling (Configuration 1a)

Figure 6.33a - Energy performance of the retrofitted building compared with current state (July 15th, Conf. 1b)
Figure 6.33b - Energy performance of the retrofitted building compared with current state (July 8-14th, Conf. 1b)

Here it is possible to see that the use of glass block according to Configuration 1b and the subsequent reduction in solar heat gain allows reducing the cooling consumption with regards to current state. For example, the peak in cooling load goes from above 600 kW, in current state, to 500 kW, in the reconfigured building, both occurring around 5:00 in the afternoon.

Differently than what observed in winter analyses, Configuration 1b allows for a reduction in cooling load also compared with Configuration 1a, even if the difference is less important (the peak in cooling here is approximately 550 kW). This is due to the decrease of the solar solar gains and also to the fact that the lower thermal transmittance of the building envelope according to Configuration 1b does not represent a significant disadvantage to the same extent as in winter analyses.

The same behaviour can be registered also in the four-month simulation: Configuration 1b introduces relevant saving compared to current state (26%), corresponding to approximately 200 MWh. Summer cooling requirements, indeed, are overall approximately four times the winter ones, so Configuration 1b introduces an important benefit to overall building performance. Comparing these results with Configuration 1a, a 13% saving (corresponding to approximately 96 MWh) can be evinced from the results.



	june	july	august	september	TOTAL
Lighting gain (MWh)	12.95	14.9	14.25	13.6	55.7
Equipment gain (MWh)	41.32	47.52	45.45	43.39	177.68
Occupancy gain (MWh)	24.65	28.35	27.11	25.88	105.99
Solar gain (MWh)	63.35	65.56	66.66	58.56	254.13
External Infiltration (MWh)	-17.58	-6.9	-3.21	-10.66	-38.35
Façade (MWh)	9,46	19,53	22,79	12,71	64,49
Heating Requirement (MWh)	0,00	0,00	0,00	0,00	0,00
Cooling Requirement (MWh)	-117.89	-155.36	-164.2	-130.69	-568.14

Figure 6.34 - Overall monthly amount of heat gains and losses (Configuration 1b)

6.5.6. Summary Considerations

By looking at the graphs in Figures 6.35 and 6.36, it is clear how the two new envelope solutions are able to reduce significantly the solar heat gain through the building envelope: in Configuration 1a this reduction is equal to 29% compared to current state value (and, in particular, to around 380 MWh/year); in Configuration 1b to 53% (around 700 MWh/year). This leads to a decrease, both in summer and winter, in terms of cooling consumption of the re-

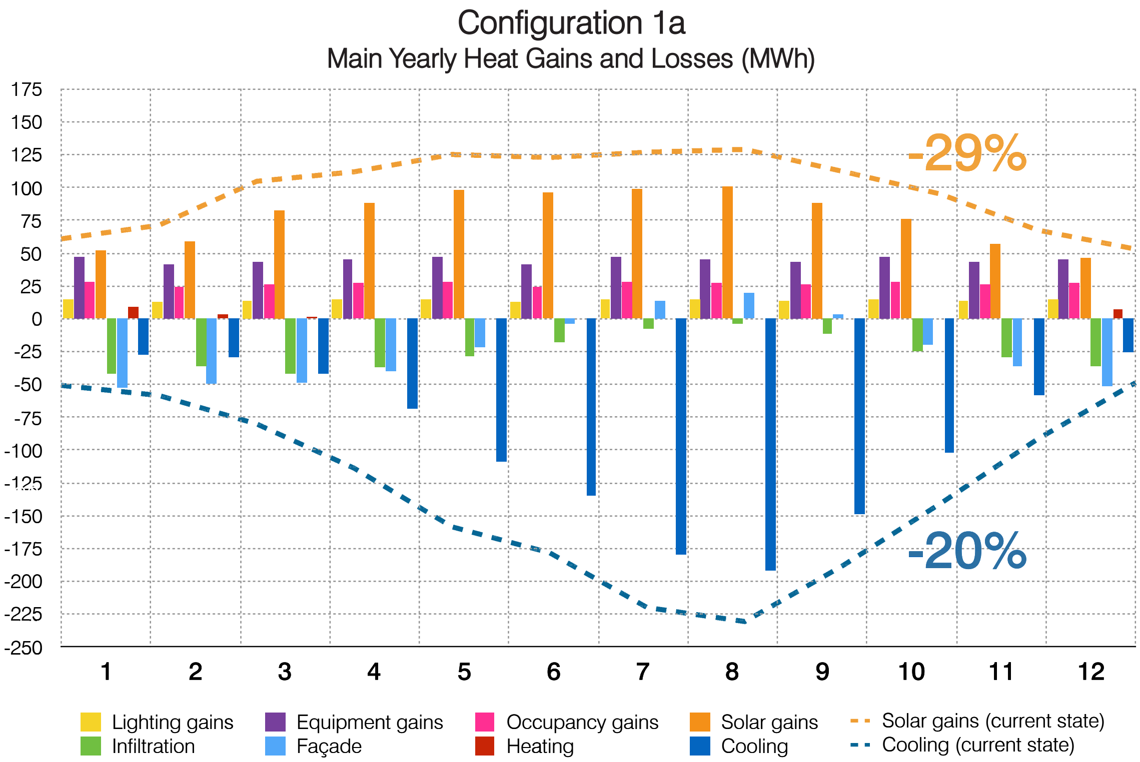


Figure 6.35 - Yearly energy balance (Conf. 1a) and comparison with current state solar gain and cooling requirement

		January	February	March	April	May	June
Solar gains (MWh)	cs	72.42	82.66	116.17	123.39	136.63	134.31
	1a	51.55	58.86	82.78	88.06	97.54	95.83
	1b	33.76	38.65	54.57	58.31	64.58	63.35
Façade (MWh)	cs	-46.69	-43.86	-45.44	-36.41	-21.23	-7.55
	1a	-52.33	-49.36	-48.36	-40.16	-21.86	-3.38
	1b	-26.55	-23.57	-20.86	-13.98	-1.30	9.46
Heating (MWh)	cs	1.71	0.43	0.13	0	0	0
	1a	9.1	2.82	1.13	0	0	0
	1b	2.61	0.6	0.2	0	0	0
Cooling (MWh)	cs	-39.21	-46.97	-68.65	-102.41	-147.03	-166.77
	1a	-27.53	-28.92	-41.26	-68.60	-109.10	-134.27
	1b	-27.92	-30.39	-40.83	-66.60	-100.10	-117.89

Table 6.10 *(continues in the next page)* - Monthly energy balance - gains (>0) and losses (<0) - related to solar gain through the envelope, façade, heating and cooling for current state (cs), configuration 1a (1a) and 1b (1b)

configured building, amounting to 20% in Configuration 1a (corresponding to a saving of about 310 MWh) and to 29% in Configuration 1b (corresponding to a saving of about 410 MWh). Overall, taking into consideration also the heating consumption, that however might be neglected with respect to cooling loads, Configuration 1b is the one linked with the largest energy saving. However, it must be highlighted that the great additional reduction in the solar heat gain that it introduces only generates a relatively small additional decrease in cooling.

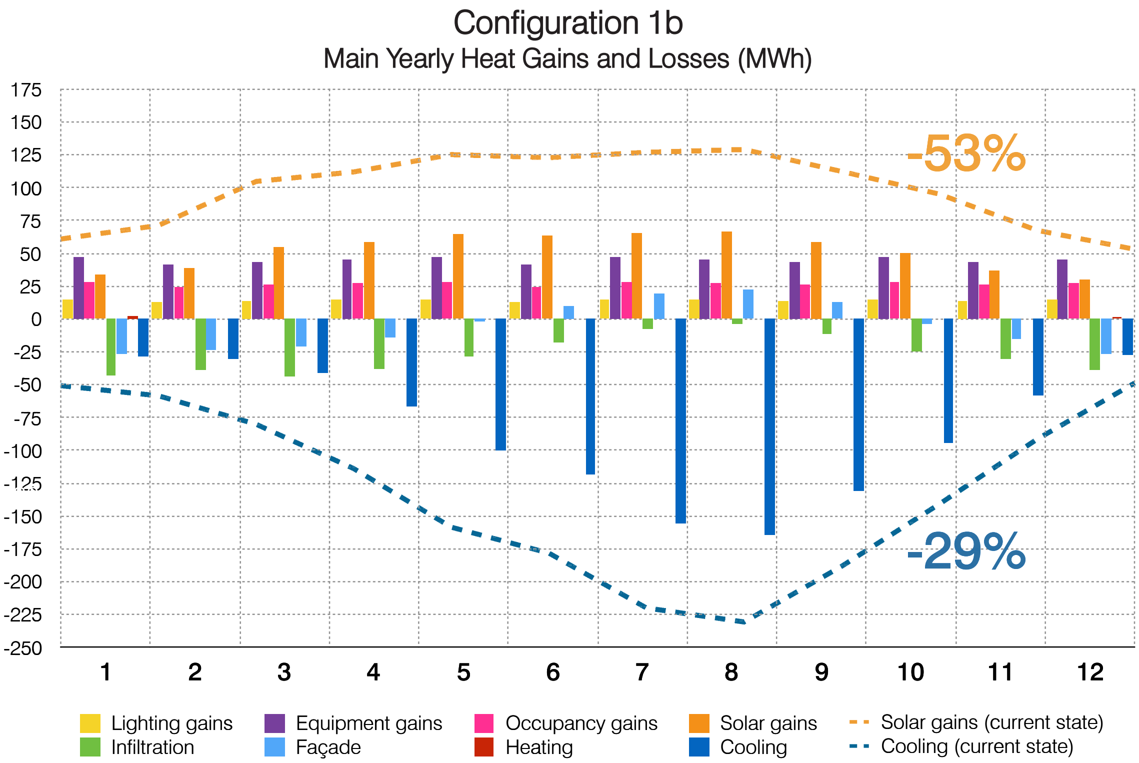


Figure 6.36 - Yearly energy balance (Conf. 1b) and comparison with current state solar gain and cooling requirement

		July	August	September	October	November	December	Total
Solar gains (MWh)	cs	138.4	140.51	123.82	106.59	79.02	64.58	1,318.5
	1a	98.86	100.4	88.38	76.07	56.33	45.99	940.65
	1b	65.56	66.66	58.56	50.43	37.03	30.11	621.56
Façade (MWh)	cs	4.7	8.74	-1.89	-19.89	-31.33	-44.04	-284.89
	1a	13.7	19.53	3.61	-20.18	-36.13	-50.91	-285.83
	1b	19.53	22.79	12.71	-3.05	-15.13	-26.09	-66.04
Heating (MWh)	cs	0	0	0	0	0.01	1.32	3.60
	1a	0	0	0	0	0.13	7.26	20.44
	1b	0	0	0	0	0.012	1.76	5.182
Cooling (MWh)	cs	-208.48	-219.12	-176.68	-129.39	-80.14	-37.33	-1,422.18
	1a	-179.64	-191.58	-148.75	-101.66	-57.51	-25.89	-1,114.71
	1b	-155.36	-164.20	-130.69	-94.30	-57.71	-27.77	-1,013.76

Table 6.10 *(continues from the previous page)* - Monthly energy balance - gains (>0) and losses (<0) - related to solar gain through the envelope, façade, heating and cooling for current state (cs), configuration 1a (1a) and 1b (1b)

This is probably due to the too high thermal insulation of the second envelope system (Configuration 1b), which in this climatic context and in this particular building (i.e. glazed office building with very low heating requirements) results counter-productive. Looking separately at the overall performance of the two façade systems, this is even more clear: the yearly thermal balance of the façade made of glass blocks according to Configuration 1a is equal to -285.83 MWh. If we look at the same parameter, in Configuration 1b simulations, it is equal to -66.04 MWh. This means that, both in Configurations 1a and 1b, throughout the year, the thermal energy E_C that crosses the building envelope from the indoor environments to the outside (cooling off the building, $E_C<0$) is higher than the thermal energy E_H moving contrarily (from the outside to the indoor environment heating up the building, $E_H>0$). In particular, in Configuration 1a, E_C is 285.83 MWh higher than E_H whereas in Configuration 1b it is "only" 66.04 MWh higher than E_H.

This big difference is actually due to the very low thermal transmittance (1.2 W/m^{2}K) of the glass block envelope according to Configuration 1b, that is way below the limit set for the area of Palermo (2.7 W/m^{2}K). Basically, the building envelope according to Configuration 1b provides a too strong resistance to the release of the heat accumulated inside the building, especially due to internal and solar gains. The great advantage related to the 53% reduction of the solar gain with respect to current state is therefore jeopardized by an excessive thermal insulation.

Having said this, it could be of interest to take into consideration a new *Configuration 1c*, where the low-e glass is substituted by a dark or tinted glazing able to reduce significantly solar gain without implying the same excessive decrease in the U value as in Configuration 1b[18].

In winter, the lower insulation of Configuration 1a translates into about 17 MWh increase in yearly consumption for heating compared to current state. In Configuration 1b, it has already been underlined that some increase (less than 2 MWh) in the heating requirement is registered as well compared to current state simulations. This is probably due to the lower solar heating occurring in early morning hours, translating into higher pre-heating needs compared to current state (despite the better thermal insulation with regards to the current state curtain wall).

Having said all that, it is of relevance to underline that U value is an important value for the definition of the energy performance of a building, especially as regards winter heating consumptions, but it can generate several problems if it is not accurately related to the actual characteristics of a building and of its context as well as to the other façade performance parameters. For example, a different result would have come out probably: from the simulation of a residential building where internal heat gains are significantly less important than in an office building, even of the same climate context; or either from the simulation of the same office building, in a colder context (such as, e.g., Northern Europe) where heating requirements are significantly more important[21] than in a context such as that of a city like Palermo. So, it is correct to state that the lower the U value, the better the insulation, but not in all cases a more insulating solution is the best option, on an overall balance, for the energy performance optimization of a building envelope, as this application demonstrated.

In this study, the natural ventilation has not been taken into account, unless of a default infiltration rate, which led to very similar yearly results among the three different sets of simulations. This obviously represents a limitation in this study and should be taken into consideration carefully in order to understand (and, eventually, further optimize) actual building energy performance. However, it was not necessary for the purpose of this work, aimed to compare different envelope solutions and to evaluate the corresponding energy-related benefits with regards to the current technical solution. The aspect of natural ventilation could be deepened as a future development of this study and, however, it would not affect the validity of the results obtained according to the purpose of this study, but rather add new information to it.

Looking at the summary reported in Table 6.11, for the already discussed reasons, only a 9% difference occurs between Configuration 1a and 1b. To this the energy production coming from the PV modules should be added (supposedly identical between the two).

	Existing Building Current state	Reconfigured building Configuration 1a	Reconfigured building Configuration 1b
Solar heat gain (MWh)	1,318.5	940.65 *-29%*	621.56 *-53%*
Heating Requirement (MWh)	3.60	20.44	5.18
Cooling Requirement (MWh)	1,422.18	1,114.71	1,013.76
Overall Heating/Cooling consumption (MWh)	1,425.78	1,135.15	1,018.94
Overall Saving for Heating/Cooling (MWh)	-	290.63 *-20%*	406.84 *-29%*

Table 6.11 - Summary Table, reporting the Solar heat gain, the heating and cooling requirement, the overall consumption and saving for current state building simulation and for the retrofitted building envelope (according to both Configurations 1a and 1b)

However, even if the second solution seems the most “energy-saving” as regards the cooling and heating requirements of the building, this small difference does not seem sufficient to justify the choice of a solution that makes use of an additional glass sheet, translating into higher costs of the product, higher weight and, subsequently, higher costs for supporting structures.

Furthermore, as already underlined, this study has not focused, in this phase, on the assessment of the daylighting performance of the new building envelopes analysed: for example, it has not been evaluated the visual comfort of occupants nor the energy required for the artificial illumination of the internal spaces. These aspects are, instead, fundamental to make the choice between one solution and another, especially because Configuration 1a and 1b have rather different visible transmittance among each other (0.272 and 0.189, respectively) and a great difference is encountered compared to current state (T_{VIS} = 0.761). This could lead to different results in terms of electricity requirements for lighting as well as, for example, visual comfort of occupants. De facto, the study of the daylighting performance is a possible future development of this work, necessary to fully understand the energy potential of the novel solution for a BIPV glazed envelope, proposed and studied in this thesis. A possible improvement compared to current state, where internal curtains are used to reduce the severe glare effects, could be found or, instead, some issues might emerge, making it necessary to adopt different technical solutions in their regards.

However, at this point, it is sufficient to underline that other works, already cited, have investigated about the feasibility of the integration of the DSC technology into semi-transparent building envelopes and demonstrated its potential also in this direction.

6.5.7. Assessment of the Photovoltaic Performance

After having analysed the energy-saving benefits related to the application of the new BIPV envelope, the performance in terms of electricity production have also been assessed. First of all, the power peak (W) of each PV-integrated glass block was calculated analytically through the following formula:

$$P_{GB} = \eta \times I_{STC} \times A_{DSC} = 5.07 \text{ W per glass block} \quad [1]$$

where:

- η is the nominal conversion efficiency of the cell (assumed equal to 7%);
- I_{STC} is the Solar Irradiance at Standard Test Conditions (STC), equal to 1000 W/m^2;
- A_{DSC} is the active area for PV conversion, which was calculated analytically through the following formula:

$$A_{DSC} = MA\% \times A_{GB} \times AA\% = 87.68\% \times (0.33 \times 0.33) \times 75\% = 0.072 \text{ m}^2 \quad [2]$$

where:

- AA% is the active area percentage with regards to glass block surface, set equal to 75%;
- MA% is the module area percentage with regards to glass block surface, equal to 87.68% in Configuration 1 (see paragraph 4.3.2.1, Figure 4.6);
- A_{GB} is the glass block surface, equal to 0.33 × 0.33 = 0.11 m^2.

Since approximately 9 glass blocks are needed for 1 square meter, this results in a power density – expressed in W/m^2 – of about 46 W/m^2. Multiplying this result by the PV-integrated glazed surfaces of the building envelope (amounting at 75% of its sun-exposed surfaces), the installed peak power (P) of the four façades, equal to 185 kW, was obtained. The yearly energy production (E, expressed in kWh/year) was calculated through the following equation:

$$E = c \times P \times I_d \times 365 \quad [3]$$

where:

- c is a correction factor, taking into account the potential losses due to aspects such as module warm-up, electrical mismatches, possible shading effects, reflections occurring on PV surfaces, etc. In crystalline silicon modules, this factor amounts at 0.75, whereas due to the already widely discussed very good operating performance of the DSC technology, in this case, it is set equal to 0.80;

- P is the total power installed (W);
- I_d is the average daily irradiation (kWh/day). This value was calculated by using the software SunSim[20], by inserting the data related to the orientation and tilt of each façade as well as the latitude of Palermo. Multiplying I_d by 365, the annual irradiation striking the PV surface of the building envelope is obtained.

The above-described procedure for the estimation of the photovoltaic performance of the building envelope is analytical and based on some assumptions (above all, the definition of a correction factor, c), which simplify the calculation but, at the same time, should be verified experimentally, in order to evaluate their actual correspondency with the operating performance of the analysed BIPV product. This is even more important, if we consider the peculiar behavior under real operating conditions of DSCs, which, for example:

- have the lowest temperature coefficient among all PV technologies;
- have their maximum efficiency in diffuse light;
- are bifacial devices, thus, when they are installed vertically, they might also benefit from artificial light;
- have a very good angular dependence, meaning that they do not suffer as much as other technologies from "non-optimal" installation angles and orientations.

Different softwares can be used for the estimation of the electricity generated by photovoltaic devices, taking also into account several loss factors. For example, Olivieri et al. (2014) used PVsyst[21] in the field of their multi-software analysis of the energy-saving potential of five different semi-transparent photovoltaic devices compared to a conventional solar control glass compliant with Spanish technical standard. PVsyst allows inserting the detailed electrical characteristics of the PV installation (including, for example, the features of the inverter) and of the solar modules, including the three different temperature coefficients defined in technical standard for photovoltaic modules certification[22]. This might turn out very useful for a full evaluation of PV modules operating performance, especially in the installations in hot climates.

Since those parameters regarding the DSC-integrated glass block components are not available at this point of the study, it has been opted for the above-explained analytical calculation. However, it is important to clarify that a more detailed evaluation of the PV performance of DSC-integrated glass block operating performance could be obtained and could represent a future development of this study aimed at the preliminary characterization of the energy performance of this product.

Finally, the estimated annual PV production (E) was calculated and, in particular, it amounts to approximately 112.5 MWh/year, corresponding to a further 8% reduction of the energy requirements compared to the very high consumption for the cooling of the building at current state, resulting into obvious savings in building management costs.

6.6. Conclusions and Future Developments

To sum up, this preliminary study allows concluding that the replacement of the building envelope with the DSC-integrated glass block components deeply studied in this work, in the two above-described configurations (1a and 1b), would generate a global yearly energy saving ranging from around 400 MWh (Configuration 1a) to 520 MWh ((Configuration 1b). This means that replacing the existing building envelope with the two aforementioned solutions, building consumption would drop from 28% to 37% every year[23]. Moreover, starting from the observation of the results, some possible margins for improvements have been already individuated, regarding, for example: a possible third glass block configuration making the most of the two analyzed (see paragraph 6.5.6.); the consideration of the benefits of a carefully scheduled natural ventilation (or, for a more simple calculation, of an increase of the infiltration rate); a more detailed and precise evaluation of the electrical output of the PV-integrated system, taking into account all the benefits regarding the operating performance of the DSC technology.

At the same time, for the sake of completeness, a daylighting analysis would be suggested, in order to evaluate and, in case, highlight the potential issues regarding the analysed product, integrated with the specific solar device considered here (Wenger et al. 2011) or, eventually, with other PV modules in order to obtain a wider spectrum of possible options, in terms of thermal, optical and electrical performance as well as aesthetic appearance.

Last but not least, indeed, a further advantage to highlight is related to the possible improvement of the appearance of the building, through the replacement of its envelope with the DSC-integrated glass blocks. A great variety of architectural results could be obtained by using different type of modules characterized by different colours and designs and by exploiting the typical modularity of the glass block for the creation of out-and-out façade drawings.

In May 2015, the groundbreaking ceremony for the Science Tower (Figure 6.37), in Graz, has been celebrated: at its completion, due to mid 2016, this 60-m tall office tower, designed by Architect Markus Pernthaler, will be world's first office building completely cladded in green DSC glazing, showcasing an attractive and innovative design that will help this building become the technological landmark of the whole Smart City Graz urban project[24]. This is an emblematic example to cite because it not only demonstrates how the implementation of these kinds of novel photovoltaic solutions into buildings is possible, but it also helps understand, besides the more quantifiable benefits in terms of energy costs and material saving, the remarkable although "immaterial" advantages that with these solutions can be generated.

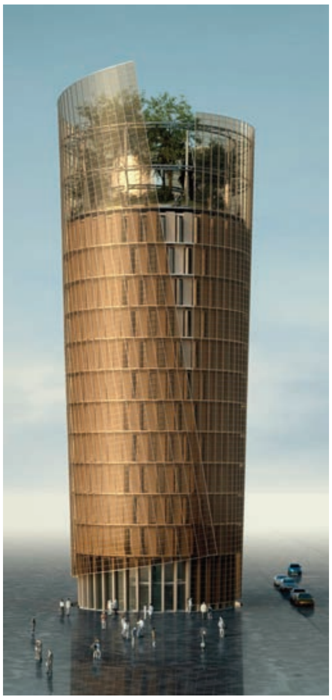


Figure 6.37 - Science Tower at Smart City Graz, Marcus Pernthaler: Project Render of the first office building entirely cladded in DSC modules (Markus Pernthaler Architekten ZT GmbH, 2013)

Notes

1) DesignBuilder Software Ltd., 2014; available at http://designbuilder.co.uk

2) The analyses continue a work started in the field of the degree theses by Milia, G. and Tutone, C.

3) Assessorato Regionale dell'Energia e dei Servizi di Pubblica Utilità (Viale Campania, 36, Palermo, http://www.google.it/maps/@38.1457837,13.3360363,17z/data=!4m2!5m1!1b1).

4) However, the glass blocks can be easily installed in front of the air-conditioning terminals and help hide them without causing any visual indoor discomfort due to colour rendering issues.

5) Cf. Milia, 2015; Tutone, 2015.

6) From the UNI TS 11300-1:2008, «*…Zona termica: Parte dell'ambiente climatizzato mantenuto a temperatura uniforme attraverso lo stesso impianto di riscaldamento, raffrescamento o ventilazione…*», i.e. the thermal zone is a part of the air-conditioned space that is maintained at uniform temperature by the same HVAC system.

7) Air infiltration rate was set to the default value of 0.5 ach (air changes per hour).

8) In this case, we are dealing with a pre-existing building and this aspect should not be of relevance.

9) The weather file contains information regarding the climatic data of a specific location, identified by its latitude and longitude. The climatic data are provided by the World Meteorological Organization (WMO).

10) Actually, the standard does not provide indications regarding the simulation period for the cooling season; it was set to these four representative months (June-September) for coherence with the study of winter season.

11) They only depend on the number of working days that can vary from one month to the others due to holydays and to the difference in the length of months. The software can simulate according to different calendars according to the location analysed.

12) The limits imposed by the Legislative Decree 311/2006 for the area of Palermo are 2.7 W/m^{2}K for glazing and 3.0 W/m^{2}K for frames.

13) The existing building envelope has a calculated U value (Uglazing 1.9 W/m^{2}K; Uframe 2.9 W/m^{2}K) below the limits imposed by the Legislative Decree 311/2006 for the area of Palermo (cf. note 12).

14) Global Horizontal Irradiation (GHI) above 1,700 kWh/m^{2}year. Cf. http:///www.solargis.info.

15) «*Palermo is one of the southern cities of Italy and one of the warmest in Europe. Its Mediterranean climate is characterized by mild winters and hot and dry summers with an average annual ambient air temperature of 18.5 °C, and approximately 2530 hours of sun-shine per year*». Cf. Pastore, 2013.

16) Such “preheating” is also needed, due to the large dimensions of the building, to avoid plants of excessive dimensions and costs, able to reach comfort temperatures in short times.

17) Despite the improved thermal insulation compared to current state curtain wall, the significantly lower solar heat gain of Configuration 1b determines an increase, in the early morning hours, of the heating requirement of the building and this explains the increase in the heating requirement, regardless of the better thermal insulation performance.

18) If we look, indeed, at the overall thermal balance of the building envelope at current state, whose U value (1.9 W/m^{2}K) is intermediate between those of glass block configurations 1a and 1b, we can see that it is closer to that of Configuration 1a and around -285 MWh.

19) Some also use the specification “heating-dominated” to refer to those climate contexts where heating requirements represent the main part (≥70%) of the buildings space conditioning needs; viceversa (cooling ≥70% of the buildings space conditioning needs), the definition “cooling-dominated” is used. The goal of this approach

is to found the climate classification not only on a location's external conditions, but also on a reference building's thermal performance (taking into account e.g. countries' building insulation requirements and building typologies). Cf. Shaan et al., 2011.

20) SunSim 7.1. Copyright (C) Francesco Groppi, 2010; available at http://www.sunsim.it.

21) www.pvsyst.com.

22) As regards the three temperature coefficients, the first (α) is related to the short-circuit current I_{SC} ot the PV module; the second (β) to the open-circuit voltage, V_{OC}; the third (δ) to the maximum power P_{max}. The three are obtained experimentally from module measurements, according to standards: IEC 61215:2005 or IEC 61646:2008.

23) Actually, the annual energy saving due to the solar gain reduction (ranging from 290-406 MWh) overshadows the annual photovoltaic production (112.5 MWh).

24) www.smartcitygraz.at.

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http://designbuilder.co.uk

Photo References

Photo 1 - Giovanni Milia, Carolina Tutone;

Photo 2 - Giovanni Milia, Carolina Tutone;

Photo 3 - Giovanni Milia, Carolina Tutone.

CONCLUSIONS _ *CONCLUSIONI*

In the last decades, a great attention has been addressed by the scientific and technical community towards the integration of renewable energies into the building stock, especially as regards photovoltaics. However, despite the significant progresses achieved and discussed in this work, the persistence of both technical and non-technical barriers — related to the acceptance, the cost-efficiency ratio, the need for a wider choice of products, the lack of technical knowledge as well as of the awareness of the money and energy-saving benefits — is still limiting the real market potential of BIPV.

Starting from these considerations, this work has intended to demonstrate the potentialities related to the integration of photovoltaic technology in architecture for the construction of zero-energy, or either plus-energy, buildings and for the retrofit of the existing building stock. At the same time, it has also underlined how complex and multidisciplinary the architectural integration process is and how it can not be reduced to the mere juxtaposition of a PV system on the roof or façade of a building. Rather, the traditional separation between technical system and building must be overcome (Scognamiglio, 2009), in the perspective of

Negli ultimi decenni, grande attenzione è stata rivolta dalla comunità tecnico-scientifica all'integrazione delle energie rinnovabili nel patrimonio edilizio, e in special modo del fotovoltaico. Eppure, nonostante i significativi progressi raggiunti, discussi all'interno di questo lavoro, la persistenza di barriere, tecniche e non — relative all'accettazione, al rapporto costo-efficienza, alla necessità di una maggiore varietà di prodotti, alla mancanza di conoscenza tecnica, alla scarsa consapevolezza dei benefici in termini di risparmio sia economico sia energetico — continua a limitare il reale potenziale di mercato del BIPV.

A partire da queste considerazioni, il presente lavoro ha inteso dimostrare le potenzialità relative all'integrazione della tecnologia fotovoltaica nell'architettura per la costruzione di "zero-energy buildings", o anche di "plus-energy buildings", e per il retrofit del patrimonio edilizio esistente. Contestualmente, esso ha anche posto l'accento su quanto complesso e multidisciplinare sia il processo d'integrazione architettonica e su come questo non possa essere ridotto a una mera giustapposizione di pannelli FV sulla copertura o sulla facciata di un edificio. Piuttosto, deve superarsi la tradizionale separazione fra edificio e impianto (Scognamiglio, 2010), nell'ottica di a whole-building approach that makes the most of available natural resources and where passive and active measures complement one another (Schittich, 2003).

Several of the case studies analyzed in this work can be considered as best practices of this approach, where photovoltaics is not only an active material able to produce energy for the satisfaction of building requirements, but also an element of aesthetic valorization and technological optimization of the building, sometimes even contributing "passively" to the energy efficiency and indoor comfort. For example, Semi-Transparent Photovoltaics (STPV), installed as technical elements of the building envelope, can be used — in place of absorbing, tinted glass or ceramic frits (Robinson & Athienitis, 2009) — in order to respond to multiple building requirements, «…*such as: solar shading in summer to avoid overheating, solar gains and thermal insulation in winter to reduce heat loads, daylighting provision to reduce lighting loads, outside view allowance to the occupants and maximum electrical output supply*…» (Olivieri et al., 2014, p. 572).

In this framework, third-generation PV technologies (Organic Photovoltaics, Dye-sensitized Solar Cells and, most recently, Perovskite Solar Cells) represent a big opportunity to transform translucent building envelopes into highly-customizable, colorful and beautiful energy generators, at low economic and environmental costs. The next two years are expected to be a turning point for these technologies, which are expected to go from lab and first pilot installations to commercialization; however, «…*further research is required to overcome efficiency,*

un approccio sistemico, "whole-building" in grado di massimizzare gli apporti delle risorse naturali e in cui strategie attive e passive si completino a vicenda (Schittich, 2003).

Molti dei casi studio analizzati in questo lavoro possono considerarsi "best practices" di quest'approccio in cui il fotovoltaico non è solo un elemento attivo capace di produrre energia per il soddisfacimento dei requisiti di un edificio, ma anche un elemento di valorizzazione estetica e ottimizzazione tecnologica dello stesso, in grado a volte anche di contribuire "passivamente" all'efficienza energetica e al comfort indoor. Per esempio, prodotti FV semitrasparenti, integrati in elementi tecnici dell'involucro edilizio, possono essere utilizzati — in luogo di vetri assorbenti, colorati o di fritte ceramiche (Robinson & Athienitis, 2009) — per rispondere a una molteplicità di requisiti «...quali: schermatura solare in estate per evitare surriscaldamenti, guadagno solare e isolamento termico in inverno per ridurre il carico di riscaldamento, apporto di luce naturale per ridurre le richieste di illuminazione, vista all'esterno da parte degli occupanti e massima produzione di elettricità...» (Olivieri et al., 2014, p. 572).

All'interno del quadro appena delineato, le tecnologie FV di terza generazione (Organic Photovoltaics, Dye-sensitized Solar Cells e, più di recente, Perovskite Solar Cells) rappresentano una grande opportunità per trasformare involucri edilizi traslucidi in generatori di energia altamente personalizzabili e colorati, a basso costo economico e ambientale. I prossimi due anni saranno un importante punto di svolta per queste tecnologie, che passeranno dal laboratorio alle prime installazioni pilota e alla commercializzazione; ad ogni modo, «...sono necessarie ulteriori ricerche per superare i limiti *stability, and manufacturing limitations before (these) emerging thin-film technologies can be considered suitable for large-scale deployment…*» (MITei, 2015, p. 147).

The thorough state-of-the-art analysis carried out in the field of third-generation photovoltaics, allows stating how the real advantages of these technologies, and especially of DSCs, actually lie in the field of building integration. This is not only supported by a rich literature, but it also proven by the agendas of most of the companies involved in DSC development and by the growing number of pilot building applications. Hence, another fundamental challenge to help growth and affirmation of DSC technology in the building and PV sectors is the development of new solutions for its integration into the building envelope. These new solutions must comply with the stricter and stricter regulations regarding the technical performance of construction products and the energy efficiency of buildings and, at the same time, make the integration process as easy as possible.

The study of the precast, prestressed and dry-assembled components made of DSC-integrated glass blocks, developed by the co-founders of SBskin. Smart Building Skin s.r.l. at the Department of Architecture of the University of Palermo, has been carried out also in the light of the above considerations.

The thermal performance of the glass block has been improved remarkably compared to the “standard” solutions existing in the market, in order to allow for its use in a greater variety of climatic contexts. The solar and optical performance were assessed by taking into account different modules and configurations of the product, obtaining a

legati a efficienza stabilità e produzione industriale, prima che (queste) tecnologie emergenti possano considerarsi pronte per un impiego su larga scala…» (MITei, 2015, p. 147).

L’approfondita analisi dello stato dell’arte condotta nell’ambito del FV di terza generazione consente di affermare come i reali vantaggi di queste tecnologie, specialmente delle DSC, siano proprio nell’ambito dell’integrazione architettonica. Ciò non solo è supportato da una ricca letteratura, ma è anche dimostrato dai piani di crescita di gran parte delle aziende attive nello sviluppo delle DSC e dal crescente numero di applicazioni pilota su edifici. Pertanto, un’importante sfida per supportare lo sviluppo e l’affermazione della tecnologia DSC nei settori edilizio e FV è legata allo sviluppo di nuove soluzioni per la sua integrazione nell’involucro degli edifici. Queste nuove soluzioni dovranno attenersi alle sempre più stringenti normative relative alle prestazioni tecniche dei prodotti da costruzione e in materia di efficienza energetica degli edifici e, al contempo, rendere il processo d’integrazione quanto più semplice possibile.

È alla luce di queste considerazioni che si è portato avanti lo studio dei pannelli precompressi e preassemblati a secco di vetromattoni integrati con DSC, sviluppati dai fondatori di SBskin. Smart Building Skin s.r.l. presso il Dipartimento di Architettura dell’Università di Palermo.

Le prestazioni di isolamento termico del vetromattone sono state migliorate significativamente rispetto alle soluzioni “standard” già presenti sul mercato, allo scopo di permetterne l’utilizzo in una più grande varietà di contesti climatici. Le prestazioni ottiche e solari sono state valutate prendendo in esame differenti moduli e configurazioni del prodotto.

wide variety in the results and allowing for the individuation of some best-performing glass block configurations. Finally, with the support of a building performance simulation software, the benefits related to the use of this solution have been evaluated on a case-study of a highly energy-demanding glazed office building in the city of Palermo. In particular, the building simulations showed the great energy-saving potential related to the use of this solution and mainly due to the solar gain reduction provided by the semi-transparent solar modules integrated into the glass blocks. The evaluated energy saving is actually even more relevant — in the specific case — than the benefits deriving from the energy generation.

In this framework, it is worth to cite Loonen et al. (2014), who stated that building performance simulation is «…*a useful additional tool in the product development of innovative building envelope components, to make the process more efficient and effective [...] routinely used for supporting informed decision-making in the building design process*…». The possibility to select, in the design phase, the most adapted balance between thermal insulation, light and solar transmission performance as well as electrical production is of great relevance for the optimization of the overall energy performance of a building, with semi-transparent BIPV glazing installed.

In this sense — despite the still present limits as regards conversion efficiency, durability, and cost — DSC technology displays an even greater potential in terms of architectural integration: it easily allows for the achievement of a great variety of colors and transparency levels, which is not only

Si è così ottenuta un'ampia varietà di risultati ed è stato inoltre possibile individuare alcune configurazioni più performanti. Infine, con il supporto di un software per la simulazione energetica, si sono valutati i benefici connessi all'utilizzo di questa soluzione nell'ambito del retrofit dell'involucro vetrato di un edificio per uffici, fortemente energivoro, sito nella città di Palermo. In particolare, le simulazioni hanno mostrato il risparmio energetico possibile grazie all'impiego della soluzione tecnica analizzata e principalmente dovuto alla riduzione degli apporti solari che i moduli solari semitrasparenti, integrati nei vetromattoni, producono. Nel caso specifico, il risparmio energetico valutato è persino più rilevante di quello connesso alla produzione di energia.

In quest'ambito, vale la pena citare Loonen et al. (2014) che hanno affermato come le simulazioni delle prestazioni degli edifici siano «...uno strumento aggiuntivo nello sviluppo di componenti innovativi per l'involucro edilizio, utile a rendere tale processo più efficiente ed efficace [...], comunemente utilizzato per supportare un più consapevole processo decisionale nell'ambito della progettazione di un edificio...». La possibilità di selezionare, in fase di progetto, l'equilibrio più adatto fra le prestazioni di isolamento termico, trasmissione luminosa e solare e produzione elettrica è un aspetto di grande rilevanza per l'ottimizzazione delle prestazioni globali di un edificio, nel cui involucro sono integrati vetri FV semitrasparenti.

In questo senso, la tecnologia DSC — malgrado gli ancora presenti limiti in termini di efficienza, durabilità e costo — presenta ulteriori vantaggi nell'ottica dell'integrazione architettonica: essa, infatti, permette facilmente di ottenere una grande varietà di colori e livelli di trasparenza. Ciò non è solo impor-

important in terms of the aesthetic result of the integration, but it also has important relapses in terms of energy performance of a building, as this work contributed to underline and demonstrate.

Starting from the results obtained in this work and from the selected DSC-integrated glass block configurations, several suggestions of research and development of further studies can be considered, such as:

- the experimental validation of the results obtained analytically and of the methodology utilized, to be conducted by means of prototype testing;
- the detailed technical design of the components in the selected configurations (as regards, for example, the electrical connections and the measures to be taken in order to ensure the mechanical, water- and air-tightness to the whole component) and the subsequent experimental verification;
- the optimization of the design and of the characteristics of the sub-components for the maximization of the performance of the DSC-integrated glass block components as technical elements of the building envelope;
- the full characterization of the photovoltaic performance (e.g. according to IEC 61646:2008) and of the constructional performance of the components (according to the basic requirements for building products defined in CPR 305/2011);
- a comprehensive analysis of the DSC-integrated glass block components by means of a Life Cycle Assessment methodology, in order to fully characterize their environmental performance.

tante per quanto riguarda il risultato estetico dell'integrazione, ma può anche avere importanti ricadute sulle prestazioni energetiche di un edificio, così come questa tesi ha contribuito a sottolineare e dimostrare.

A partire dai risultati ottenuti in questo lavoro e dalle configurazioni di vetromattone integrato con DSC selezionate, si possono prefigurare una serie di possibili sviluppi di studio e ricerca, come, ad esempio:

- *la validazione sperimentale dei risultati ottenuti analiticamente e della metodologia utilizzata, da effettuarsi attraverso test di prototipi;*
- *il progetto tecnologico dettagliato dei componenti nelle configurazioni selezionate (per quanto riguarda, ad esempio, le connessioni elettriche e le misure da adottare al fine di garantire la resistenza meccanica, la tenuta all'acqua e all'aria dei componenti) e la successiva verifica sperimentale;*
- *l'ottimizzazione del progetto e delle caratteristiche dei sub-componenti del pannello per la massimizzazione delle prestazioni dei vetromattoni integrati con DSC in quanto elementi tecnici dell'involucro edilizio;*
- *la completa caratterizzazione delle prestazioni fotovoltaiche (ad es., secondo lo standard IEC 61646:2008) e tecnico-costruttive dei componenti (sulla base dei "requisiti essenziali" per i prodotti edilizi definiti nella CPR 305/2011);*
- *un'analisi esauriente dei pannelli in vetromattone integrato con DSC attraverso una metodologia di Life Cycle Assessment per una completa caratterizzazione delle loro prestazioni ambientali.*

The above-listed possible developments, some of which are already in progress, have to be undertaken by involving competences from different fields as well as glass block, DSC and plastic material manufacturers. Due to the novelty of the product, to its complex nature — contextually of building and photovoltaic element — and to the absence of a harmonized standard regulation for BIPV products, certification entities and/or authorized laboratories will also have to be involved for the definition of its certification process.

All in all, further multidisciplinary studies are required for this innovative component to be completely engineered and eventually commercialized. However, this work aims to represent an important phase for the technological definition and optimization of this product as well as for the individuation and quantification of the main benefits related to its use as technical element of energy-efficient, translucent, and multifunctional building envelopes, both in the field of new construction and renovation works.

Gli sviluppi possibili appena sopra elencati, alcuni dei quali sono già stati intrapresi, devono essere portati avanti attraverso il coinvolgimento di competenze provenienti da diversi settori nonché dei produttori di vetromattone, DSC e materie plastiche. A causa della novità del prodotto, della sua complessa natura di elemento edilizio e FV al contempo, e dell'assenza di normative armonizzate per i prodotti BIPV, anche gli enti certificatori e/o i laboratori autorizzati dovranno essere coinvolti nella definizione del processo di certificazione.

Saranno necessari ulteriori sviluppi multidisciplinari per la completa ingegnerizzazione e la commercializzazione di questo prodotto innovativo per il BIPV. Questo lavoro si propone di rappresentare un importante momento per la definizione e l'ottimizzazione tecnologica di questo prodotto nonché per l'individuazione e la quantificazione dei principali benefici connessi al suo impiego come elemento tecnico di involucri edilizi traslucidi, multifunzionali e sostenibili, sia nell'ambito di edifici di nuova costruzione che del recupero dell'esistente.

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APPENDIX TO CHAPTER 5

Analysis of the 4 patented configurations (Wenger's DSC)

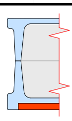
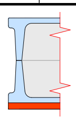
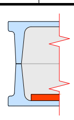
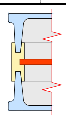
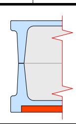
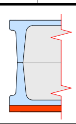
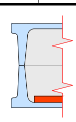
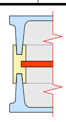
			COMSOL		WINDOW												
			U-value		CENTER OF GLASS DATA				OPTICAL DATA								
			2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3
WENGER 100%	1	V 	2,4	2,6	2,2	0,426	37,00%	287	11,47%	8,54%	14,70%	26,55%	18,20%	19,06%	51,73%	-	3,53%
		A	2,9	2,9	2,7	0,443	38,60%	302	11,47%	8,54%	14,70%	26,55%	18,20%	19,06%	51,73%	-	3,53%
	2	V 	2,4	2,6	2,2	0,426	37,00%	287	11,47%	8,54%	14,70%	26,55%	18,20%	19,06%	51,73%	-	3,53%
		A	2,9	2,9	2,7	0,443	38,60%	302	11,47%	8,54%	14,70%	26,55%	18,20%	19,06%	51,73%	-	3,53%
	3	V 	2,5	2,7	2,2	0,430	37,40%	290	11,44%	5,21%	11,99%	26,50%	15,75%	17,26%	54,23%	-	3,52%
		A	3,0	3,0	2,7	0,448	39,00%	305	11,44%	5,21%	11,99%	26,50%	15,75%	17,26%	54,23%	-	3,52%
	4	V 	1,7	1,6	1,4	0,537	46,70%	351	10,21%	15,13%	15,13%	24,19%	20,80%	20,80%	10,93%	40,85%	3,22%
		A	2,0	1,7	1,7	0,534	46,50%	352	10,21%	15,13%	15,13%	24,19%	20,80%	20,80%	10,93%	40,85%	3,22%
WENGER 75%	1	V 	2,4	2,6	2,2	0,492	42,80%	329	26,61%	8,92%	14,63%	32,08%	11,48%	13,76%	52,80%	-	3,64%
		A	2,9	2,9	2,7	0,510	44,40%	344	26,61%	8,92%	14,63%	32,08%	11,48%	13,76%	52,80%	-	3,64%
	2	V 	2,4	2,6	2,2	0,492	42,80%	329	26,61%	8,92%	14,63%	32,08%	11,48%	13,76%	52,80%	-	3,64%
		A	2,9	2,9	2,7	0,510	44,40%	344	26,61%	8,92%	14,63%	32,08%	11,48%	13,76%	52,80%	-	3,64%
	3	V 	2,5	2,7	2,2	0,497	43,20%	332	26,55%	5,99%	12,25%	32,03%	8,85%	11,84%	55,50%	-	3,63%
		A	3,0	3,0	2,7	0,516	44,90%	347	26,55%	5,99%	12,25%	32,03%	8,85%	11,84%	55,50%	-	3,63%
	4	V 	1,7	1,6	1,4	0,598	52,10%	390	23,80%	15,61%	15,61%	29,34%	15,65%	15,65%	10,41%	41,26%	3,34%
		A	2,0	1,7	1,7	0,596	51,90%	391	23,80%	15,61%	15,61%	29,34%	15,65%	15,65%	10,41%	41,26%	3,34%

Table 5A.1 *(continues in the next page)* - Detailed summary table of the analyses of the four configurations integrated with Wenger's DSC module, containing all relevant parameters obtained

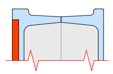
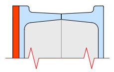
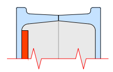
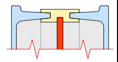
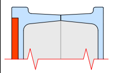
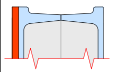
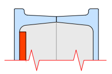
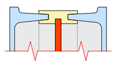
				WINDOW															
				TEMPERATURE DATA (°C) U-value NFRC								TEMPERATURE DATA (°C) SHGC							
				Outside Air	Layer 1		Layer 2		Layer 3		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Inside Air
					out	in	out	in	out	in			out	in	out	in	out	in	
WENGER 100%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	49,6	51,3	38,0	37,4	-	-	24,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	49,6	51,3	38,0	37,4	-	-	24,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	53,4	36,6	36,1	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,3	38,4	37,8	-	-	24,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	44,6	45,7	75,6	75,6	45,3	44,3	24,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	44,6	45,7	67,2	67,2	45,3	44,3	24,0
WENGER 75%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	48,2	49,9	35,4	35,0	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	47,5	49,0	36,9	36,4	-	-	24,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	48,2	49,9	35,4	35,0	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	47,5	49,0	36,9	36,4	-	-	24,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	49,0	50,8	35,8	35,3	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	48,3	49,8	37,3	36,8	-	-	24,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	43,6	44,6	71,2	71,2	43,5	42,6	24,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	43,5	44,5	63,6	63,6	43,6	42,7	24,0

Table 5A.1 *(continues from the previous page)* - Detailed summary table of the analyses of the four configurations integrated with Wenger's DSC module, containing all relevant parameters obtained

Analysis of the 4 patented configurations (Green g2e)

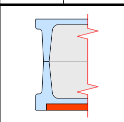
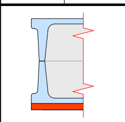
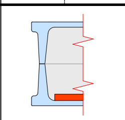
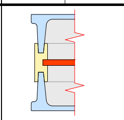
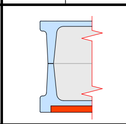
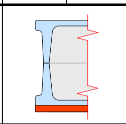
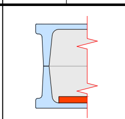
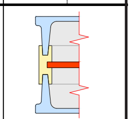
				COMSOL U-value 2D	COMSOL U-value 3D	CENTER OF GLASS DATA U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	WINDOW OPTICAL DATA Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3
G2E GREEN 100%	1	V		2,4	2,6	2,2	0,394	34,30%	267	20,04%	9,13%	15,12%	22,33%	11,11%	13,99%	63,81%	-	2,74%
		A		2,9	2,9	2,7	0,417	36,30%	285	20,04%	9,13%	15,12%	22,33%	11,11%	13,99%	63,81%	-	2,74%
	2	V		2,4	2,6	2,2	0,394	34,30%	267	20,04%	9,13%	15,12%	22,33%	11,11%	13,99%	63,81%	-	2,74%
		A		2,9	2,9	2,7	0,417	36,30%	285	20,04%	9,13%	15,12%	22,33%	11,11%	13,99%	63,81%	-	2,74%
	3	V		2,5	2,7	2,2	0,400	34,80%	271	19,97%	5,25%	11,97%	22,29%	7,48%	11,33%	67,48%	-	2,74%
		A		3,0	3,0	2,7	0,425	37,00%	290	19,97%	5,25%	11,97%	22,29%	7,48%	11,33%	67,48%	-	2,74%
	4	V		1,7	1,6	1,4	0,548	47,70%	328	17,73%	15,66%	15,66%	20,85%	14,75%	14,75%	10,29%	51,53%	2,57%
		A		2,0	1,7	1,7	0,545	47,40%	359	17,73%	15,66%	15,66%	20,85%	14,75%	14,75%	10,29%	51,53%	2,57%
G2E GREEN 75%	1	V		2,4	2,6	2,2	0,459	39,90%	308	33,03%	9,57%	14,93%	28,91%	11,18%	13,82%	56,86%	-	3,05%
		A		2,9	2,9	2,7	0,479	41,70%	324	33,03%	9,57%	14,93%	28,91%	11,18%	13,82%	56,86%	-	3,05%
	2	V		2,4	2,6	2,2	0,459	39,90%	308	33,03%	9,57%	14,93%	28,91%	11,18%	13,82%	56,86%	-	3,05%
		A		2,9	2,9	2,7	0,479	41,70%	324	33,03%	9,57%	14,93%	28,91%	11,18%	13,82%	56,86%	-	3,05%
	3	V		2,5	2,7	2,2	0,464	40,40%	312	32,95%	6,66%	12,56%	28,86%	7,92%	11,44%	60,17%	-	3,05%
		A		3,0	3,0	2,7	0,486	42,30%	329	32,95%	6,66%	12,56%	28,86%	7,92%	11,44%	60,17%	-	3,05%
	4	V		1,7	1,6	1,4	0,584	50,80%	381	29,48%	16,28%	16,28%	26,83%	15,09%	15,09%	10,30%	44,93%	2,85%
		A		2,0	1,7	1,7	0,582	50,60%	382	29,48%	16,28%	16,28%	26,83%	15,09%	15,09%	10,30%	44,93%	2,85%

Table 5A.2 *(continues in the next page)* - Detailed summary table of the analyses of the four configurations integrated with the green g2e module, containing all relevant parameters obtained

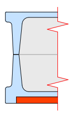
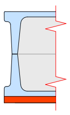
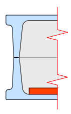
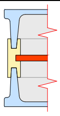
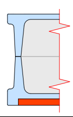
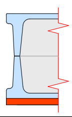
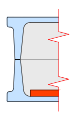
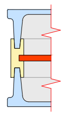
			WINDOW																	
				TEMPERATURE DATA (°C) U-value NFRC								TEMPERATURE DATA (°C) SHGC							
				Outside Air	Layer 1		Layer 2		Layer 3		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Inside Air
					out	in	out	in	out	in			out	in	out	in	out	in	
G2E GREEN 100%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	25,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	26,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	27,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	28,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	29,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	30,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	31,0
G2E GREEN 75%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	32,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	33,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	34,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	35,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	36,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	37,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	38,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	39,0

Table 5A.2 *(continues from the previous page)* - Detailed summary table of the analyses of the four configurations integrated with the green g2e module, containing all relevant parameters obtained

Analysis of the 4 patented configurations (Red g2e)

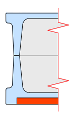
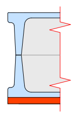
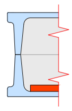
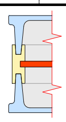
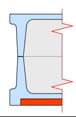
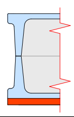
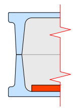
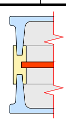
				COMSOL		WINDOW												
				U-value		CENTER OF GLASS DATA				OPTICAL DATA								
				2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3
G2E RED 100%	1	V		2,4	2,6	2,2	0,410	35,70%	278	11,12%	8,40%	14,60%	23,85%	11,27%	13,85%	61,77%	-	3,10%
		A		2,9	2,9	2,7	0,433	37,60%	295	11,12%	8,40%	14,60%	23,85%	11,27%	13,85%	61,77%	-	3,10%
	2	V		2,4	2,6	2,2	0,410	35,70%	278	10,38%	8,40%	14,60%	23,85%	11,27%	13,85%	61,77%	-	3,10%
		A		2,9	2,9	2,7	0,433	37,60%	295	10,38%	8,40%	14,60%	23,85%	11,27%	13,85%	61,77%	-	3,10%
	3	V		2,5	2,7	2,2	0,416	36,20%	281	11,09%	5,02%	11,85%	23,83%	8,04%	11,49%	65,03%	-	3,10%
		A		3,0	3,0	2,7	0,440	38,20%	299	11,09%	5,02%	11,85%	23,83%	8,04%	11,49%	65,03%	-	3,10%
	4	V		1,7	1,6	1,4	0,558	48,50%	364	9,91%	15,02%	15,02%	22,45%	15,09%	15,09%	10,36%	49,19%	2,91%
		A		2,0	1,7	1,7	0,554	48,20%	364	9,91%	15,02%	15,02%	22,45%	15,09%	15,09%	10,36%	49,19%	2,91%
G2E RED 75%	1	V		2,4	2,6	2,2	0,471	41,00%	316	26,36%	8,92%	14,65%	30,03%	11,26%	13,72%	55,39%	-	3,22%
		A		2,9	2,9	2,7	0,459	39,90%	312	26,36%	8,92%	14,65%	30,03%	11,26%	13,72%	55,39%	-	3,22%
	2	V		2,4	2,6	2,2	0,471	41,00%	316	26,36%	8,92%	14,65%	30,03%	11,26%	13,72%	55,39%	-	3,22%
		A		2,9	2,9	2,7	0,459	39,90%	312	26,36%	8,92%	14,65%	30,03%	11,26%	13,72%	55,39%	-	3,22%
	3	V		2,5	2,7	2,2	0,477	41,50%	319	26,30%	5,96%	12,23%	29,99%	8,22%	11,50%	58,48%	-	3,32%
		A		3,0	3,0	2,7	0,497	43,20%	336	26,30%	5,96%	12,23%	29,99%	8,22%	11,50%	58,48%	-	3,32%
	4	V		1,7	1,6	1,4	0,592	51,50%	386	23,58%	15,61%	15,61%	28,02%	15,20%	15,20%	10,33%	43,34%	3,11%
		A		2,0	1,7	1,7	0,590	51,30%	387	23,58%	15,61%	15,61%	28,02%	15,20%	15,20%	10,33%	43,34%	3,11%

Table 5A.3 *(continues in the next page)* - Detailed summary table of the analyses of the four configurations integrated with the red g2e module, containing all relevant parameters obtained

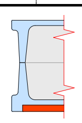
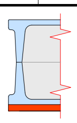
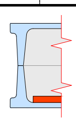
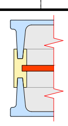
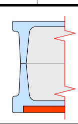
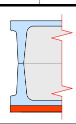
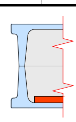
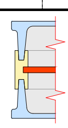
				WINDOW															
				TEMPERATURE DATA (°C) U-value NFRC								TEMPERATURE DATA (°C) SHGC							
				Outside Air	Layer 1		Layer 2		Layer 3		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Inside Air
					out	in	out	in	out	in			out	in	out	in	out	in	
G2E RED 100%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	24,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	25,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	26,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	27,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	28,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	29,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	30,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	31,0
G2E RED 75%	1	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	32,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	33,0
	2	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	34,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	35,0
	3	V		-18,0	-15,2	-14,1	11,0	11,4	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	36,0
		A		-18,0	-13,9	-12,4	7,1	7,7	-	-	21,0	32,0	50,5	52,4	36,3	35,8	-	-	37,0
	4	V		-18,0	-16,3	-16,0	0,5	0,8	14,7	14,9	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	38,0
		A		-18,0	-15,4	-15,0	-1,4	-0,9	11,8	12,2	21,0	32,0	50,5	52,4	36,3	35,8	35,3	34,8	39,0

Table 5A.3 *(continues from the previous page)* - Detailed summary table of the analyses of the four configurations integrated with the red g2e module, containing all relevant parameters obtained

New thermally-optimized and PV-integrated Configurations (Wenger's DSC 100%)

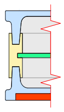
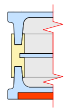
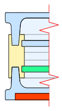
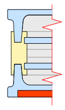
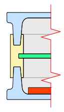
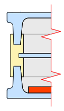
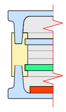
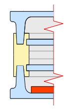
				COMSOL		WINDOW													
				U-value		CENTER OF GLASS DATA				OPTICAL DATA									
				2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3	Abs4
Configuration 1 - WENGER 100%	1.01	V		0,9	1,4	0,2	0,242	21,00%	155	10,03%	8,68%	17,67%	15,31%	23,10%	29,66%	56,35%	3,50%	1,74%	-
		A		1,2	1,6	1,4	0,270	23,50%	179	10,03%	8,68%	17,67%	15,31%	23,10%	29,66%	56,35%	3,50%	1,74%	-
	1.02	V		1,7	1,8	1,3	0,362	31,50%	240	10,36%	8,81%	20,07%	22,50%	19,08%	21,94%	52,46%	3,03%	2,93%	-
		A		1,9	2,0	1,9	0,375	32,60%	251	10,36%	8,81%	20,07%	22,50%	19,08%	21,94%	52,46%	3,03%	2,93%	-
	1.03	V		1,1	1,5	0,2	0,231	20,10%	147	9,08%	8,88%	22,55%	13,25%	23,46%	29,36%	56,65%	3,65%	1,51%	1,48%
		A		1,4	1,7	1,1	0,243	21,10%	161	9,08%	8,88%	22,55%	13,25%	23,46%	29,36%	56,65%	3,65%	1,51%	1,48%
	1.04	V		1,5	1,7	0,9	0,319	27,70%	210	9,39%	9,30%	24,57%	19,16%	19,72%	24,13%	53,00%	3,17%	2,52%	2,44%
		A		1,7	1,8	1,4	0,330	28,70%	219	9,39%	9,30%	24,57%	19,16%	19,72%	24,13%	53,00%	3,17%	2,52%	2,44%
Configuration 3 - WENGER 100%	3.01	V		0,9	1,4	0,2	0,240	20,90%	153	9,99%	5,35%	15,53%	15,21%	20,59%	28,61%	59,00%	3,47%	1,73%	-
		A		1,2	1,6	1,4	0,271	23,60%	179	9,99%	5,35%	15,53%	15,21%	20,59%	28,61%	59,00%	3,47%	1,73%	-
	3.02	V		1,7	1,8	1,3	0,364	31,70%	242	10,31%	5,47%	17,82%	22,43%	16,63%	20,54%	55,01%	3,02%	2,92%	-
		A		1,9	2,0	1,9	0,378	32,90%	264	10,31%	5,47%	17,82%	22,43%	16,63%	20,54%	55,01%	3,02%	2,92%	-
	3.03	V		1,1	1,5	0,2	0,229	20,00%	146	9,03%	5,55%	20,76%	13,16%	20,94%	28,51%	59,32%	3,62%	1,50%	1,46%
		A		1,4	1,7	1,1	0,243	21,20%	161	9,03%	5,55%	20,76%	13,16%	20,94%	28,51%	59,32%	3,62%	1,50%	1,46%
	3.04	V		1,5	1,7	0,9	0,320	27,80%	211	9,33%	5,69%	22,68%	19,07%	17,26%	23,03%	55,57%	3,16%	2,51%	2,43%
		A		1,7	1,8	1,4	0,331	28,80%	220	9,33%	5,69%	22,68%	19,07%	17,26%	23,03%	55,57%	3,16%	2,51%	2,43%

Table 5A.4 *(continues in the next page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

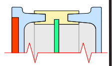
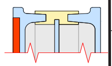
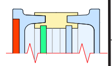
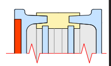
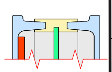
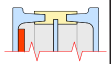
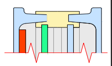
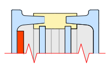
				WINDOW																			
				TEMPERATURE DATA (°C) U-value NFRC										TEMPERATURE DATA (°C) SHGC									
				Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air
					out	in	out	in	out	in	out	in			out	in	out	in	out	in	out	in	
Configuration 1 - WENGER 100%	1.01	V		-18,0	-17,8	-17,7	18,4	18,4	20,0	20,1	-	-	21,0	32,0	52,8	55,5	36,6	36,5	29,6	29,4	-	-	24,0
		A		-18,0	-16,2	-15,5	-5,2	-4,9	14,3	14,6	-	-	21,0	32,0	51,5	53,9	41,1	40,9	32,4	32,0	-	-	24,0
	1.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	49,9	52,1	45,5	45,3	33,4	33,0	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	49,4	51,4	44,8	44,6	34,5	34,1	-	-	24,0
	1.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	53,0	55,8	45,8	45,8	39,7	39,5	30,5	30,3	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	52,3	54,9	47,4	47,3	40,8	40,6	32,0	31,7	24,0
	1.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	51,2	53,7	51,4	51,3	44,4	44,2	32,7	32,4	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	50,8	53,1	50,2	50,1	43,5	43,3	33,7	33,3	24,0
Configuration 3 - WENGER 100%	3.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	53,7	56,6	36,6	36,6	29,6	29,4	-	-	24,0
		A		-18,0	-16,2	-15,5	-5,2	-4,9	14,3	14,6	-	-	21,0	32,0	55,3	58,2	42,9	42,7	33,2	32,8	-	-	24,0
	3.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	50,7	53,0	46,1	45,9	33,6	33,2	-	-	24,0
		A		-18,0	-15,5	-14,5	-1,0	-0,7	12,0	12,3	-	-	21,0	32,0	50,2	52,3	45,4	45,1	34,8	34,4	-	-	24,0
	3.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	53,9	56,8	45,9	45,8	39,7	39,5	30,5	30,3	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	53,2	55,9	47,9	47,7	41,0	40,8	32,1	31,8	24,0
	3.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	52,1	54,6	52,0	52,0	44,9	44,7	32,9	32,5	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	51,6	54,1	50,9	50,8	44,0	43,7	33,9	33,5	24,0

Table 5A.4 *(continues from the previous page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

New thermally-optimized and PV-integrated configurations (Wenger's DSC 75%)

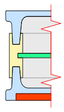
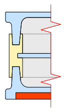
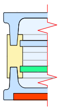
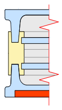
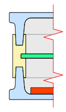
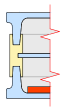
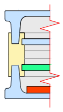
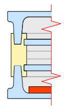
				COMSOL		WINDOW													
				U-value		CENTER OF GLASS DATA				OPTICAL DATA									
				2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3	Abs4
Configuration 1 - WENGER 75%	1.01	V		0,9	1,4	0,2	0,306	26,60%	195	23,57%	9,21%	17,66%	20,29%	16,33%	26,69%	57,52%	4,01%	1,85%	-
		A		1,2	1,6	1,4	0,333	29,00%	219	23,57%	9,21%	17,66%	20,29%	16,33%	26,69%	57,52%	4,01%	1,85%	-
	1.02	V		1,7	1,8	1,3	0,423	36,80%	279	24,19%	9,58%	20,03%	27,56%	12,51%	17,76%	53,78%	3,13%	3,03%	-
		A		1,9	2,0	1,9	0,437	38,00%	290	24,19%	9,58%	20,03%	27,56%	12,51%	17,76%	53,78%	3,13%	3,03%	-
	1.03	V		1,1	1,5	0,2	0,291	25,30%	185	21,49%	9,72%	22,72%	17,81%	16,81%	27,06%	58,01%	4,18%	1,61%	1,58%
		A		1,4	1,7	1,1	0,302	26,20%	198	21,49%	9,72%	22,72%	17,81%	16,81%	27,06%	58,01%	4,18%	1,61%	1,58%
	1.04	V		1,5	1,7	0,9	0,376	32,70%	246	22,10%	10,12%	24,54%	23,80%	13,26%	20,85%	54,52%	3,27%	2,61%	-
		A		1,7	1,8	1,4	0,387	33,60%	255	22,10%	10,12%	24,54%	23,80%	13,26%	20,85%	54,52%	3,27%	2,61%	-
Configuration 3 - WENGER 75%	3.01	V		0,9	1,4	0,2	0,305	26,50%	194	23,50%	6,28%	15,76%	20,19%	13,63%	25,72%	60,37%	3,98%	1,84%	-
		A		1,2	1,6	1,4	0,334	29,10%	219	23,50%	6,28%	15,76%	20,19%	13,63%	25,72%	60,37%	3,98%	1,84%	-
	3.02	V		1,7	1,8	1,3	0,425	37,00%	280	24,09%	6,64%	18,04%	27,47%	9,87%	16,28%	56,52%	3,12%	3,02%	-
		A		1,9	2,0	1,9	0,440	38,30%	292	24,09%	6,64%	18,04%	27,47%	9,87%	16,28%	56,52%	3,12%	3,02%	-
	3.03	V		1,1	1,5	0,2	0,289	25,20%	184	21,39%	6,78%	20,96%	17,71%	14,10%	26,27%	60,88%	4,15%	1,59%	1,57%
		A		1,4	1,7	1,1	0,302	26,30%	198	21,39%	6,78%	20,96%	17,71%	14,10%	26,27%	60,88%	4,15%	1,59%	1,57%
	3.04	V		1,5	1,7	0,9	0,377	32,80%	247	21,97%	7,18%	22,87%	23,70%	10,61%	19,70%	57,29%	3,26%	2,60%	2,53%
		A		1,7	1,8	1,4	0,389	33,80%	256	21,97%	7,18%	22,87%	23,70%	10,61%	19,70%	57,29%	3,26%	2,60%	2,53%

Table 5A.5 *(continues in the next page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

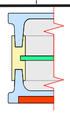
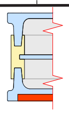
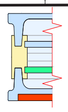
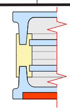
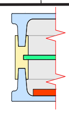
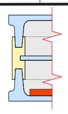
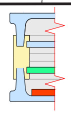
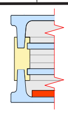
Configuration				WINDOW – TEMPERATURE DATA (°C) U-value NFRC										TEMPERATURE DATA (°C) SHGC									
				Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air
					out	in	out	in	out	in	out	in			out	in	out	in	out	in	out	in	
Configuration 1 - WENGER 75%	1.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	53,2	56,0	37,9	37,8	30,1	29,9	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,6	14,1	14,4	-	-	21,0	32,0	52,0	54,5	41,9	41,7	32,8	32,4	-	-	24,0
	1.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	50,4	52,6	45,9	45,7	33,6	33,2	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	49,8	51,9	45,2	45,0	34,8	34,3	-	-	24,0
	1.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	53,5	56,4	47,9	47,8	41,1	40,9	31,1	30,8	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	52,9	55,6	48,7	48,6	41,7	41,4	32,5	32,1	24,0
	1.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	51,8	54,3	52,1	52,0	44,9	44,7	33,0	32,6	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	51,3	53,7	50,8	50,7	44,0	43,8	33,9	33,6	24,0
Configuration 3 - WENGER 75%	3.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	54,2	57,1	37,9	37,8	30,1	29,9	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,6	14,1	14,4	-	-	21,0	32,0	52,9	55,5	42,3	42,1	32,9	32,6	-	-	24,0
	3.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	51,3	53,6	46,6	46,4	33,8	33,4	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	50,7	52,8	45,9	45,6	35,0	34,6	-	-	24,0
	3.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	54,5	57,5	47,9	47,8	41,1	40,9	31,1	30,8	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	53,8	56,6	49,1	49,0	41,9	41,7	32,6	32,3	24,0
	3.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	52,7	55,3	52,8	52,7	45,4	45,2	33,1	32,8	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	52,2	54,7	51,6	51,4	44,5	44,2	34,2	33,7	24,0

Table 5A.5 *(continues from the previous page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

New thermally-optimized and PV-integrated configurations (Green g2e 100%)

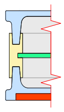
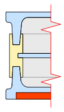
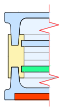
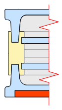
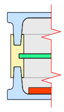
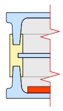
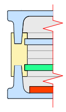
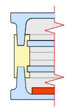
				COMSOL		WINDOW													
				U-value		CENTER OF GLASS DATA				OPTICAL DATA									
				2D	3D	U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3	Abs4
Configuration 1 - G2E GREEN 100%	1.01	V		0,9	1,4	0,2	0,220	19,10%	140	17,87%	9,27%	18,06%	14,17%	14,01%	26,40%	67,56%	2,87%	1,39%	-
		A		1,2	1,6	1,4	0,260	22,60%	173	17,87%	9,27%	18,06%	14,17%	14,01%	26,40%	67,56%	2,87%	1,39%	-
	1.02	V		1,7	1,8	1,3	0,327	28,50%	219	18,29%	9,48%	20,43%	19,05%	11,65%	17,94%	64,68%	2,36%	2,27%	-
		A		1,9	2,0	1,9	0,302	30,00%	198	18,29%	9,48%	20,43%	19,05%	11,65%	17,94%	64,68%	2,36%	2,27%	-
	1.03	V		1,1	1,5	0,2	0,209	18,20%	134	16,34%	9,54%	22,88%	12,38%	14,24%	26,84%	68,00%	2,99%	1,21%	1,18%
		A		1,4	1,7	1,1	0,232	20,20%	154	16,34%	9,54%	22,88%	12,38%	14,24%	26,84%	68,00%	2,99%	1,21%	1,18%
	1.04	V		1,5	1,7	0,9	0,286	24,80%	210	16,76%	9,77%	24,88%	16,34%	12,04%	20,99%	65,33%	2,46%	1,95%	1,88%
		A		1,7	1,8	1,4	0,300	26,10%	219	16,76%	9,77%	24,88%	16,34%	12,04%	20,99%	65,33%	2,46%	1,95%	1,88%
Configuration 3 - G2E GREEN 100%	3.01	V		0,9	1,4	0,2	0,220	19,10%	140	17,79%	5,39%	15,56%	14,11%	10,35%	25,40%	71,30%	2,85%	1,39%	-
		A		1,2	1,6	1,4	0,263	22,90%	175	17,79%	5,39%	15,56%	14,11%	10,35%	25,40%	71,30%	2,85%	1,39%	-
	3.02	V		1,7	1,8	1,3	0,331	28,80%	221	18,18%	5,59%	17,82%	18,99%	8,02%	15,90%	68,38%	2,35%	2,26%	-
		A		1,9	2,0	1,9	0,350	30,50%	235	21,97%	5,59%	17,82%	18,99%	8,02%	15,90%	68,38%	2,35%	2,26%	-
	3.03	V		1,1	1,5	0,2	0,209	18,20%	133	16,24%	5,66%	20,80%	12,32%	10,58%	26,03%	71,75%	2,98%	1,20%	1,17%
		A		1,4	1,7	1,1	0,234	20,30%	155	16,24%	5,66%	20,80%	12,32%	10,58%	26,03%	71,75%	2,98%	1,20%	1,17%
	3.04	V		1,5	1,7	0,9	0,288	25,10%	191	16,62%	5,88%	22,69%	16,27%	8,40%	19,40%	69,05%	2,45%	1,95%	1,87%
		A		1,7	1,8	1,4	0,303	26,40%	202	16,62%	5,88%	22,69%	16,27%	8,40%	19,40%	69,05%	2,45%	1,95%	1,87%

Table 5A.6 *(continues in the next page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

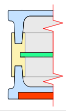
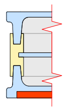
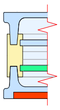
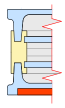
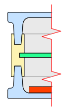
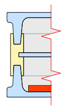
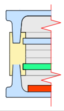
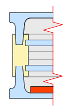
				WINDOW																			
				TEMPERATURE DATA (°C) U-value NFRC										TEMPERATURE DATA (°C) SHGC									
				Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air
					out	in	out	in	out	in	out	in			out	in	out	in	out	in	out	in	
Configuration 1 - G2E GREEN 100%	1.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	56,7	60,1	35,4	35,3	28,9	28,8	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,7	14,1	14,4	-	-	21,0	32,0	55,1	58,1	42,0	41,8	32,6	32,3	-	-	24,0
	1.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	53,7	56,4	47,5	47,3	33,7	33,4	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	53,0	55,5	46,9	46,6	35,2	34,7	-	-	24,0
	1.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	57,0	60,0	43,5	43,5	37,8	37,7	29,7	29,5	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	56,0	59,1	48,2	48,0	40,9	40,7	32,0	31,7	24,0
	1.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	55,0	58,0	53,5	53,4	45,1	44,9	32,7	32,3	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	54,5	57,3	52,5	52,3	44,5	44,2	33,9	33,5	24,0
Configuration 3 - G2E GREEN 100%	3.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	58,0	61,6	35,5	35,4	29,0	28,8	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,7	14,1	14,4	-	-	21,0	32,0	56,4	59,4	42,6	42,4	32,9	32,5	-	-	24,0
	3.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	54,9	57,7	48,4	48,1	34,1	33,7	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	54,2	56,8	47,8	47,5	35,6	35,1	-	-	24,0
	3.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	58,3	61,9	43,7	43,6	37,9	37,8	29,7	29,5	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	57,2	60,5	48,8	48,6	41,3	41,1	32,2	31,8	24,0
	3.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	56,3	59,4	54,6	54,4	45,8	45,5	32,9	32,5	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	55,7	58,7	53,5	53,3	45,1	44,9	34,2	33,7	24,0

Table 5A.6 *(continues from the previous page)* - Detailed summary table of the analyses, containing all relevant parameters derived from the analyses

New thermally-optimized and PV-integrated Configurations (Green g2e 75%)

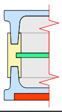
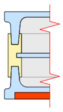
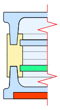
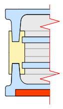
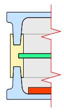
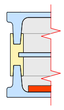
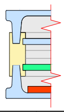
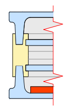
				COMSOL U-value 2D	COMSOL U-value 3D	WINDOW – CENTER OF GLASS DATA U-Value EN673	SC	SHGC	Rel. ht. Gain (W/m2)	WINDOW – OPTICAL DATA Tv	Rf,vis	Rb,vis	Tsol	Rf,sol	Rb,sol	Abs1	Abs2	Abs3	Abs4
Configuration 1 - G2E GREEN 75%	1.01	V		0,9	1,4	0,2	0,288	25,10%	184	29,44%	9,92%	17,91%	19,43%	14,43%	26,37%	61,02%	3,53%	1,59%	-
		A		1,2	1,6	1,4	0,321	27,90%	211	29,44%	9,92%	17,91%	19,43%	14,43%	26,37%	61,02%	3,53%	1,59%	-
	1.02	V		1,7	1,8	1,3	0,391	34,00%	259	30,14%	10,48%	20,28%	24,96%	11,98%	17,82%	57,91%	2,62%	2,53%	-
		A		1,9	2,0	1,9	0,406	35,50%	271	30,14%	10,48%	20,28%	24,96%	11,98%	17,82%	57,91%	2,62%	2,53%	-
	1.03	V		1,1	1,5	0,2	0,274	23,80%	174	26,94%	10,65%	22,76%	17,15%	14,84%	26,82%	61,58%	3,69%	1,38%	1,36%
		A		1,4	1,7	1,1	0,290	25,20%	190	26,94%	10,65%	22,76%	17,15%	14,84%	26,82%	61,58%	3,69%	1,38%	1,36%
	1.04	V		1,5	1,7	0,9	0,346	30,10%	227	27,62%	11,25%	24,75%	21,68%	12,58%	20,90%	58,70%	2,74%	2,18%	2,12%
		A		1,7	1,8	1,4	0,358	31,20%	237	27,62%	11,25%	24,75%	21,68%	12,58%	20,90%	58,70%	2,74%	2,18%	2,12%
Configuration 3 - G2E GREEN 75%	3.01	V		0,9	1,4	0,2	0,288	25,00%	183	29,35%	7,00%	16,03%	19,36%	11,14%	25,58%	64,41%	3,51%	1,59%	-
		A		1,2	1,6	1,4	0,323	28,10%	212	29,35%	7,00%	16,03%	19,36%	11,14%	25,58%	64,41%	3,51%	1,59%	-
	3.02	V		1,7	1,8	1,3	0,394	34,30%	261	30,01%	7,56%	18,31%	24,88%	8,72%	16,01%	61,25%	2,62%	2,53%	-
		A		1,9	2,0	1,9	0,411	35,70%	274	30,01%	7,56%	18,31%	24,88%	8,72%	16,01%	61,25%	2,62%	2,53%	-
	3.03	V		1,1	1,5	0,2	0,273	23,80%	174	26,81%	7,72%	21,19%	17,07%	11,55%	26,18%	64,99%	3,66%	1,38%	1,35%
		A		1,4	1,7	1,1	0,302	25,30%	198	26,81%	7,72%	21,19%	17,07%	11,55%	26,18%	64,99%	3,66%	1,38%	1,35%
	3.04	V		1,5	1,7	0,9	0,348	30,30%	228	27,46%	8,31%	23,10%	21,59%	9,31%	19,50%	62,08%	2,73%	2,18%	2,11%
		A		1,7	1,8	1,4	0,361	31,40%	239	27,46%	8,31%	23,10%	21,59%	9,31%	19,50%	62,08%	2,73%	2,18%	2,11%

Table 5A.7 *(continues in the next page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

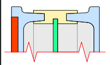
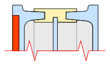
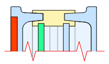
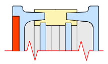
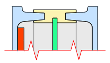
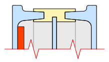
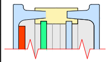
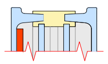
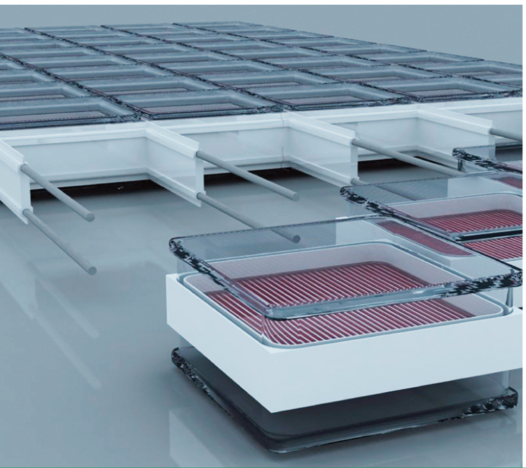
				WINDOW																				
				TEMPERATURE DATA (°C) U-value NFRC										TEMPERATURE DATA (°C) SHGC										
				Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air	Outside Air	Layer 1		Layer 2		Layer 3		Layer 4		Inside Air
					out	in	out	in	out	in	out	in			out	in	out	in	out	in	out	in	
Configuration 1 - G2E GREEN 75%	1.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	54,4	57,5	36,7	36,7	29,6	29,4	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,6	14,1	14,4	-	-	21,0	32,0	53,1	55,8	41,9	41,6	32,6	32,3	-	-	24,0
	1.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	51,6	54,0	46,3	46,0	33,4	33,1	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	51,0	53,2	45,7	45,4	34,7	34,3	-	-	24,0
	1.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	54,7	57,8	45,9	45,8	39,6	39,4	30,4	30,2	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	54,0	56,8	48,3	48,2	41,2	41,0	32,2	31,9	24,0
	1.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	52,9	55,7	52,2	52,1	44,5	44,3	32,6	32,3	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	52,5	55,1	51,2	51,0	43,8	43,6	33,7	33,3	24,0
Configuration 3 - G2E GREEN 75%	3.01	V		-18,0	-17,8	-17,7	18,4	18,5	20,0	20,1	-	-	21,0	32,0	55,6	58,8	36,8	36,7	29,6	29,4	-	-	24,0
		A		-18,0	-16,1	-15,4	4,4	4,6	14,1	14,4	-	-	21,0	32,0	54,2	57,0	42,3	42,1	32,8	32,5	-	-	24,0
	3.02	V		-18,0	-16,3	-15,6	0,7	0,9	14,7	14,9	-	-	21,0	32,0	52,7	55,2	47,0	46,8	33,7	33,3	-	-	24,0
		A		-18,0	-15,5	-14,5	-0,9	-0,6	12,0	12,4	-	-	21,0	32,0	52,0	54,4	46,4	46,1	35,1	34,6	-	-	24,0
	3.03	V		-18,0	-17,8	-17,7	16,9	17,0	18,5	18,5	20,1	20,1	21,0	32,0	55,9	59,2	46,0	45,9	39,6	39,5	30,4	30,2	24,0
		A		-18,0	-16,6	-16,0	0,5	0,6	8,2	8,4	15,7	15,9	21,0	32,0	55,1	58,1	48,9	48,8	41,6	41,4	32,3	32,0	24,0
	3.04	V		-18,0	-16,8	-16,3	-4,2	-4,0	6,6	6,8	16,3	16,5	21,0	32,0	54,1	57,0	53,2	53,0	45,1	44,9	32,8	32,8	24,0
		A		-18,0	-16,2	-15,5	-5,0	-4,8	4,9	5,1	14,4	14,6	21,0	32,0	53,5	56,3	52,1	51,9	44,4	44,2	33,9	33,5	24,0

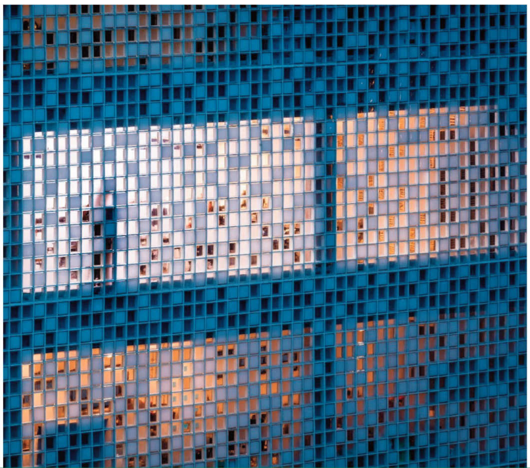
Table 5A.7 *(continues from the previous page)* - Detailed summary table of the analyses, containing all relevant parameters obtained

The present work deals with the architectural integration of photovoltaics (PV) for the energy retrofit of the existing building stock and the construction of Zero Energy Buildings. The main objective is the study of strategies and technologies for the integration of photovoltaics in buildings, particularly with regard to third-generation solar devices and, subsequently, the definition of a novel, multifunctional component for the building envelope integrated with Dye-sensitized Solar Cells (DSC).

In the first part of the work, the research focused on an in-depth analysis of products of the Building Integrated Photovoltaic (BIPV) market, underlining differences, limits and potentialities of each PV technology in the perspective of the architectural integration. Contextually, numerous case-study buildings have been analyzed, thus allowing for some considerations regarding new trends observed and possible developments.

The second part regards the technological optimization and energy performance analysis of a novel translucent component for BIPV, developed at the Department of Architecture of the University of Palermo: namely, a multifunctional panel made of glass blocks integrated with third-generation Dye-sensitized Solar Cells. Novel thermally optimized glass block configurations, integrated with DSC modules with different colors and transparency levels, have been analyzed with the support of different softwares, in order to assess their thermal, optical, and electrical performance. Subsequently, the benefits deriving from the installation of this product in place of the glazed façades of an office building located in Palermo, have also been assessed with the support of a software for building performance simulation. The aim is to evaluate its energy saving and production potential as well as to make some considerations regarding its applicability as technical element of sustainable building roofs and façades.





Marco Morini (1988), graduated in 2012 cum laude in Architectural Engineering at the University of Palermo. His main research interests are in the building technology and energy-efficient architecture. He developed work and study experiences between Europe and USA. Some of his works are published in conference proceedings, books and magazines. Since 2013, he has also been co-founder of the technological start-up SBskin. Smart Building Skin s.r.l. which deals with innovative and energy-efficient building components.