UNIVERSITÀ DEGLI STUDI DI PALERMO

Dottorato in Energia e Tecnologie dell'Informazione
Dipartimento di Ingegneria
Settore Scientifico Disciplinare – Fisica Tecnica Ambientale (ING-IND/11)

SIMULATION AND EXPERIMENTAL METHODS FOR IMPROVING ENERGY EFFICIENCY, ENVIRONMENTAL PERFORMANCE AND RESILIENCE OF SINGLE AND CLUSTERED GROUPS OF BUILDINGS

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CICLO XXXIII
ANNO CONSEGUIMENTO TITOLO 2021

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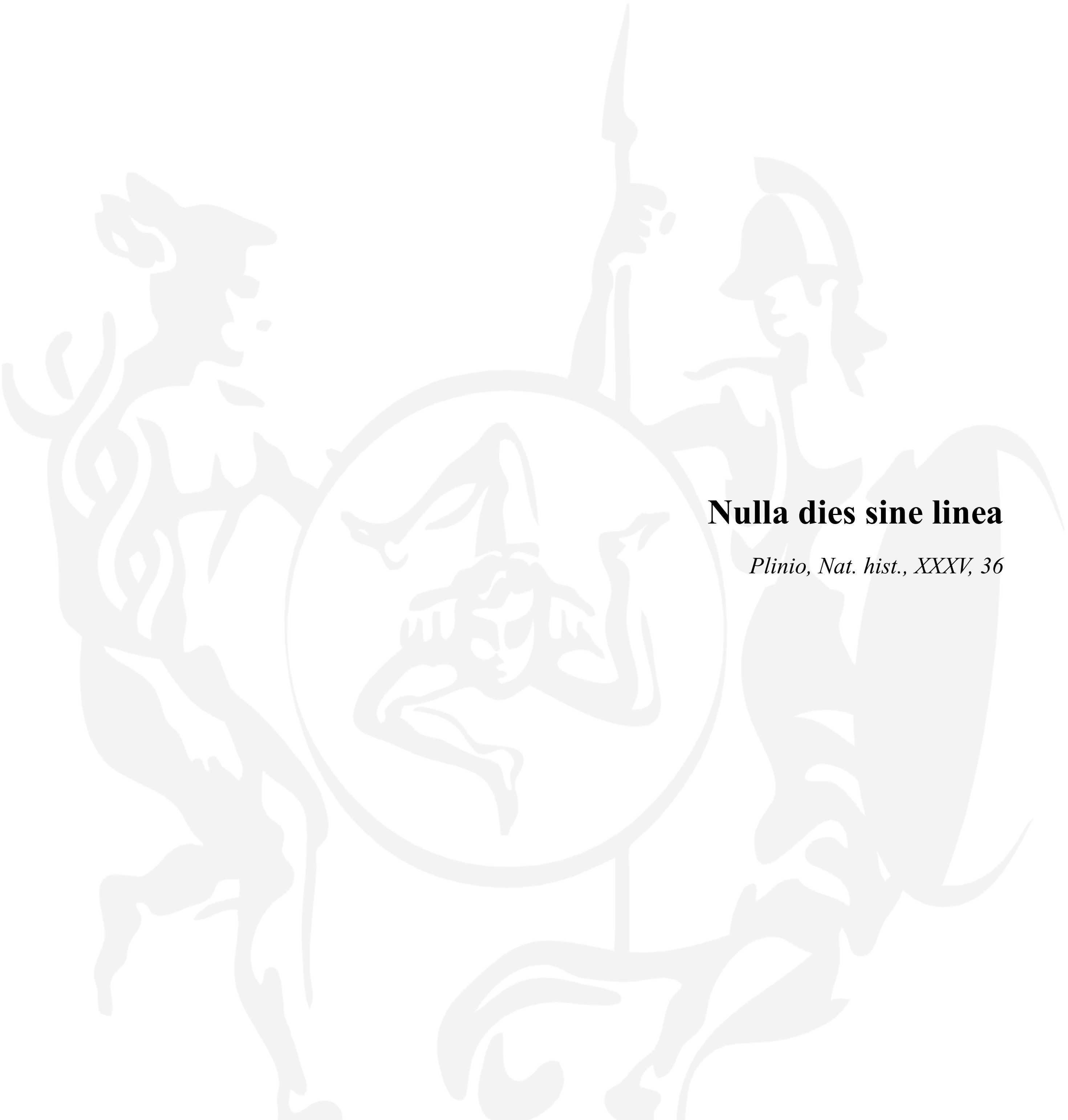
PROGRAMMA OPERATIVO



Nulla dies sine linea

Plinio, Nat. hist., XXXV, 36

Abstract

Energy consumption in the building sector is responsible for 36% of the energy use worldwide (corresponding to 39% of the total energy-related CO_2 emissions), while at the European level the building sector accounts for a share of the total energy consumption comprised between 25% and 40% (corresponding to about 35% of the overall CO_2 emissions throughout Europe). Concerning the Italian context, instead, such figures stand at about 40% and 17.5% for the energy consumption and for the CO_2 emissions, respectively. In light of this, much attention has been paid, at global, European and single countries (national) levels on the important aspects regarding the reduction of energy consumption and the related decrease of greenhouse gases emissions in order to improve the environmental performance and the resilience of the building sector, both by the political and legislative bodies and by the scientific community.

Despite the effort spent in putting into effect such actions, in recent years, the energy consumption in the building sector has experienced an increase, particularly in Italy. That is why more exertion in advancing the current measures and finding new innovative strategies to improve energy efficiency and resilience of buildings are of paramount importance.

The research work carried out during the PhD course, and presented in this doctoral thesis, arises precisely from this context and from the desire to contribute to the question. To this end, strategies and solutions aimed at improving the energy efficiency, environmental performance and resilience of buildings, were assessed in detail by means of both experimental and modeling approaches. Accordingly, a number of case studies were designed and conducted to estimate how the adoption of some proposed interventions could impact the energy consumption, the indoor thermal comfort and contribute to the reduction of the CO_2 emissions of buildings. In doing this, two important aspects influencing the afore-mentioned strategies and solutions were also considered, namely, the effect of the climatic conditions characterizeing the considered sites and the spatial scale at which they are applied, from the single building to a wider group of them, and how such perspective may influence the surrounding areas.

The outcomes of the carried-out work put in evidence how accurate planning, construction and management of buildings, according to the peculiarities of the sites in which they are located, can contribute to reduce the energy and environmental burden of the building sector and at the same time help in the enhancement of urban resilience. Proper solution sets can, in fact, enable the building resilience against the outdoor stresses and simultaneously guarantee a regenerative indoor environment.

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Supporting institution

The present doctoral thesis was elaborated over the three-year period (from November 2017 to December 2020) of the XXXIII Cycle PhD course in “Energy and Information Technologies” of the University of Palermo, within the Department of Engineering under the supervision of Prof. Gianluca Scaccianoce. As well as, during the six-months research visiting period (from January to July 2020) at the Luxembourg Institute od Science and Technology – LIST, working within the Environmental Sustainability Assessment and Circularity (SUSTAIN) Unit of the Environmental Research & Innovation Department (ERIN), under the supervision of Senior R&T Associate Antonino Marvuglia PhD. Moreover, part of the work was developed within the framework of the participation to the STSM (Short Term Scientific Mission) of the COST (European Cooperation in Science & Technology) Action CA16114 RESTORE - REthinking Sustainability TOwards a Regenerative Economy – Funded by the Horizon 2020 Framework Programme of the European Union, with the project “Vegetated roofs as regenerative tools for the mitigation of the building energy consumption and the improvement of the indoor comfort”, a summary of which can be found online at the following link: https://www.eurestore.eu/short-term-scientific-missions-stsm/stsms-for-grant-period-three/.

Summary

The research work carried out during the PhD course consisted in assessing strategies and solutions aimed at improving the energy efficiency, environmental performance and resilience of buildings, by means of both experimental and simulation approaches. Part of the work regarded, in particular, two important aspects influencing the afore-mentioned strategies and solutions: (i) the effect of the climatic conditions characterizeing the considered sites; (ii) the spatial scale at which they are applied, from the single building to a wider clustered group of dwellings, and how such perspective may influence the surrounding areas. Moreover, a specific attention was given to two distinct types of buildings that represent an important reality in the Italian construction panorama, for both economic and historical reasons, namely tourism and historical buildings.

The innovative aspect of the work presented in the dissertation is mainly represented by the integration of multidisciplinary tools to evaluate the social, energetic and environmental outcomes of the proposed solutions on different spatial scales, and also considering diverse climatic conditions.

Therefore, given the multidisciplinarity of the performed studies, and in order of rendering as complete a picture as possible of the outcomes of the research work carried out during the PhD course, each of the fifteen chapters contained in the dissertation is based on and will follow the typical format of a paper (including abstract, introduction, methodology, results, discussion, conclusions, appendices and references). Such research papers, where the undersigned PhD candidate participated as co-author and in which all authors contributed equally, have either been published, are under review in international peer-reviewed indexed journals or have been recently submitted for publication, and/or have also been presented in a series of international scientific conferences.

- Cirrincione, L., La Gennusa, M., Marino, C., Nucara, A., Peri, G., Rizzo, G., Scaccianoce, G., *Retrofitting existing buildings by means of innovative envelope components: Low-impacting new assemblies* (2020), 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140532, pp. 500-505. DOI: https://doi.org/10.1109/melecon48756.2020.9140532. [*Chapter 1*].

- Fabbri, K., Tronchin, L., Barbieri, F., Merli, F., Manfren, M., Gennusa, M.L., Peri, G., Cirrincione, L., Panzera, M.F., *On the hygrothermal behavior of coconuts fiber insulators on green roofs* (2020) Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020, art. no. 9160779. DOI: https://doi.org/10.1109/eeeic/icpseurope49358.2020.9160779. [*Chapter 2*].

- Cirrincione, L., Gennusa, M.L., Marino, C., Nucara, A., Marvuglia, A., Peri, G., *Passive components for reducing environmental impacts of buildings: analysis of an experimental green roof* (2020) 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140546, pp. 494-499. DOI: https://doi.org/10.1109/melecon48756.2020.9140546. [*Chapter 3*].

- Laura Cirrincione, Giorgia Peri, *Covering the Gap for an Effective Energy and Environmental Design of Green Roofs: Contributions from Experimental and Modelling Researches* (2020), “Rethinking sustainability towards a regenerative economy”, Andreucci, M.B., Marvuglia, A., Baltov, M., Hansen, P., Reith, A., (eds.), Springer, *IN PRESS*. [*Chapter 4*].

- Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., Aprile, S., *Green roofs as effective tools for improving the indoor comfort levels of buildings-an application to a case study in Sicily* (2020), Applied Sciences (Switzerland), 10 (3), art. no. 893. DOI: https://doi.org/10.3390/app10030893. [*Chapter 5*].

- La Gennusa, M., Macaluso, R., Mosca, M., Scaccianoce, G., Massaro, F., Cirrincione, L., *An experimental study on relationship between LED lamp characteristics and non-image-forming*, (2017) Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2017, art. no. 7977546. DOI: https://doi.org/10.1109/eeeic.2017.7977546. [*Chapter 6*].

- Cirrincione, L., Macaluso, R., Mosca, M., Scaccianoce, G., Costanzo, S., *Study of Influence of the LED Technologies on Visual and Subjective/Individual Aspects*, (2018) Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018, art. no. 8494515. DOI: https://doi.org/10.1109/eeeic.2018.8494515. [*Chapter 7*].

- Cirrincione, L., Malara, C., Marino, C., Nucara, A., Peri, G., Pietrafesa, M., *Effect of the thermal storage dimensions on the performances of solar photovoltaic-thermal system*, (2020), Renewable Energy, 162, pp. 2004-2018. DOI: https://doi.org/10.1016/j.renene.2020.09.140. [*Chapter 8*].

- Cirrincione, L., La Gennusa, M., Peri, G., Rizzo, G., Scaccianoce, G., *Considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions*, (2020) Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020, art. no. 9160783. DOI: https://doi.org/10.1109/eeeic/icpseurope49358.2020.9160783. [*Chapter 9*].

- Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., *Comparing indoor performances of a building equipped with four different roof configurations in 65 Italian sites*, (2020) 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140533, pp. 488-493. DOI: https://doi.org/10.1109/melecon48756.2020.9140533. [*Chapter 10*].

- Cirrincione, L., Marvuglia, A., Peri, G., Rizzo, G., Scaccianoce, G., *The European standards for energy efficiency in buildings: An analysis of the evolution with reference to a case study*, (2019) AIP Conference Proceedings, 2191, art. no. 020049. DOI: https://doi.org/10.1063/1.5138782. [*Chapter 11*].

- Bisegna, F., Cirrincione, L., Lo Casto, B.M., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., *Fostering the energy efficiency through the energy savings: The case of the University of Palermo*, (2019) Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, art. no. 8783774. DOI: https://doi.org/10.1109/eeeic.2019.8783774. [*Chapter 12*].

- Cirrincione, L., Marvuglia, A., Scaccianoce, G., *How effective will vegetated roofs be in enhancing buildings' climate resilience in 60 years?*. WILL BE SUBMITTED SHORTLY. [*Chapter 13*].

- Cirrincione, L., Nucara, A., Peri, G., Rizzo, G., Scaccianoce, G., *Two operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical services providers*, (2020) Journal of Cultural Heritage, 41, pp. 200-210. DOI: https://doi.org/10.1016/j.culher.2019.07.012. [*Chapter 14*].

- Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., *Towards nearly zero energy and environmentally sustainable agritourisms: The effectiveness of the application of the European ecolabel brand*, (2020) Applied Sciences (Switzerland), 10 (17), art. no. 5741. DOI: https://doi.org/10.3390/app10175741. [*Chapter 15*].

In addition, part of the research activities performed during the PhD course have also been object of collaboration to some other works that have not been included in the dissertation, as follows:

- Laura Cirrincione, Patrizia Ferrante, Maria La Gennusa, Giorgia Peri, Gianluca Scaccianoce, *Thermo-hygrometry and IAQ Related Measurements of the Indoor Physical Conditions of Exhibition Halls for Complying International Rules and Standards*, 13th SDEWES Conference, September 30–October 4 2018, Palermo, Italy (13th Conference on Sustainable Development of Energy, Water and Environment Systems).

- Matilde Pietrafesa, Laura Cirrincione, Giorgia Peri, Gianfranco Rizzo, Gianluca Scaccianoce, *Suitability of Some Existing Damage Indexes for Regulating Contracts Between Curators of Museums and HVAC Maintenance and Management Companies*, 13th SDEWES Conference, September 30–October 4 2018, Palermo, Italy (13th Conference on Sustainable Development of Energy, Water and Environment Systems).

- Laura Cirrincione, Cristina Malara, Concettina Marino, Antonino Nucara, Giorgia Peri, Matilde Pietrafesa, *PV/T Systems: Effect of Both Storage Features and Load Configuration*, (2019), 16th IBPSA International Conference and Exhibition, Internarional Building Performance Simulation Association, 2019. DOI: https://doi.org/10.26868/25222708.2019.210548.

- Cirrincione, L., Scaccianoce, G., Scrudato, M., Pietrafesa, M., Rizzo, G., *Tunnel fire active protection: Improving ventilation system*, (2019) Journal of Physics: Conference Series, 1224 (1), art. no. 012005. DOI: https://doi.org/10.1088/1742-6596/1224/1/012005.

- Pietrafesa, M., Cirrincione, L., Peri, G., Rizzo, G., Scaccianoce, G., *Suitability of Some Existing Damage Indexes for Assessing Agreements in Maintenance and Management of Museum Climatization Systems*, (2020) Journal of Sustainable Development of Energy, Water and Environment Systems, 8 (2), pp. 396-409. DOI: https://doi.org/10.13044/j.sdewes.d7.0293.

- Laura Cirrincione, Giorgia Peri, Gianfranco Rizzo, and Gianluca Scaccianoce, *Leading agritourism facilities along nearly zero energy paths: proposal of an easy-to-use evaluation method*, (2020), E3S Web of

Conferences, 197 art. no. 02004. DOI: https://doi.org/10.1051/e3sconf/202019702004.

- Fabio Cibella, Laura Cirrincione, Paolo Colombo, Gaspare Drago, Alessandra Longo, Valeria Longo, Silvia Ruggieri, Giorgia Peri, Gianluca Scaccianoce, *A Case Study of the Indoor Air Quality in Schools Belonging to an Area of the Sicilian Island Interested by the Presence of Petrochemical Rifineries*, 15th ROOMVENT 2020 Conference, Energy efficient ventilation for healthy future buildings, Virtual Conference on February 15th, 2021. ACCEPTED PAPER.

- L. Cirrincione, G. Peri, G. Rizzo, G. Scaccianoce, *On the possible inclusion of sustainable mobility practices within the actions eligible by universities for achieving energy efficiency credits*. WILL BE SUBMITTED SHORTLY.

Furthermore, the PhD candidate has been given the opportunity to:

- review several papers for international scientific journals;

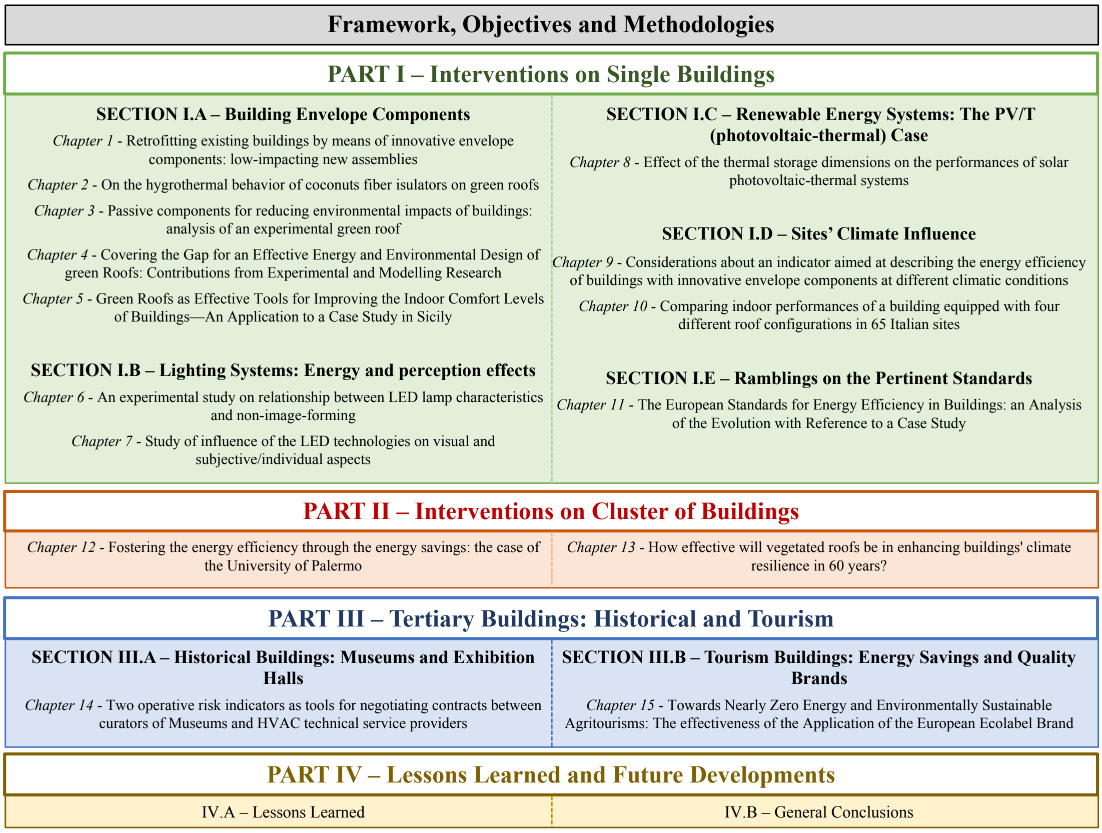
- take part, as didactic support, in the teaching activities regarding the exercises of the courses of *Fisica Tecnica Ambientale* and *Gestione delle Risorse Energetiche nel Territorio* of the bachelor and master courses in *Ingegneria per l'Ambiente e il Territorio*, and of the courses of *Progetti di Impianti per l'Edilizia* ed *Impianti Tecnici* of the master course in *Ingegneria dei Sistemi Edilizi* of the University of Palermo;

- co-supervising a few theses works for the bachelor degree in courses in *Ingegneria per l'Ambiente e il Territorio*, and of the master degree in *Ingegneria dei Sistemi Edilizi* of the University of Palermo.

Structure of the Dissertation

As previously mentioned the dissertation shows – within a general framework aimed at the greening of antropically organized contexts – a series of multidisciplinary applications regarding methods and solutions for improving energy efficiency, environmental performance and resilience of buildings on different spatial scales (from single to clustered group of dwellings) and climatic contexts, which represent the main results of the research work carried out during the three years PhD course.

The structure of the dissertation is organized into fifteen chapters distributed among three main parts, preceded by an introductory section which sets the framework, objectives and methodologies at the base of the PhD research work, and followed by a conclusive fourth part highlighting the main findings and possible future developments of the carried-out work. The following Figure A presents a flow chart that can be used throughout the reading of this manuscript as a conceptual map of the dissertation.



Framework, Objectives and Methodologies

PART I – Interventions on Single Buildings

SECTION I.A – Building Envelope Components

Chapter 1 - Retrofitting existing buildings by means of innovative envelope components: low-impacting new assemblies

Chapter 2 - On the hygrothermal behavior of coconuts fiber isulators on green roofs

Chapter 3 - Passive components for reducing environmental impacts of buildings: analysis of an experimental green roof

Chapter 4 - Covering the Gap for an Effective Energy and Environmental Design of green Roofs: Contributions from Experimental and Modelling Research

Chapter 5 - Green Roofs as Effective Tools for Improving the Indoor Comfort Levels of Buildings—An Application to a Case Study in Sicily

SECTION I.B – Lighting Systems: Energy and perception effects

Chapter 6 - An experimental study on relationship between LED lamp characteristics and non-image-forming

Chapter 7 - Study of influence of the LED technologies on visual and subjective/individual aspects

SECTION I.C – Renewable Energy Systems: The PV/T (photovoltaic-thermal) Case

Chapter 8 - Effect of the thermal storage dimensions on the performances of solar photovoltaic-thermal systems

SECTION I.D – Sites' Climate Influence

Chapter 9 - Considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions

Chapter 10 - Comparing indoor performances of a building equipped with four different roof configurations in 65 Italian sites

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PART II – Interventions on Cluster of Buildings

Chapter 12 - Fostering the energy efficiency through the energy savings: the case of the University of Palermo

Chapter 13 - How effective will vegetated roofs be in enhancing buildings' climate resilience in 60 years?

PART III – Tertiary Buildings: Historical and Tourism

SECTION III.A – Historical Buildings: Museums and Exhibition Halls

Chapter 14 - Two operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical service providers

SECTION III.B – Tourism Buildings: Energy Savings and Quality Brands

Chapter 15 - Towards Nearly Zero Energy and Environmentally Sustainable Agritourisms: The effectiveness of the Application of the European Ecolabel Brand

PART IV – Lessons Learned and Future Developments

IV.A – Lessons Learned

IV.B – General Conclusions

Figure A. Conceptual map of the dissertation.

Framework, Objectives, Methodologies and References

Energy efficient and resilient buildings are crucial items for a future that is environmentally sustainable, economically viable, as well as socially and culturally ethical, within the climate change context and inside the urban environment.

In this ambit, in fact resilience can be defined as *"the ability of an individual, a household, a community, a country or a region to withstand, to adapt, and to quickly recover from stresses and shocks"* [1]. Hence, a comprehensive urban resilience is strictly connected to the that concerning the buildings as individual entities.

Buildings are indeed part of a wider urban context of which they represent important spots where most of the antropic functions are explicated. Urban context which in the last few years has been increasingly subject to external forcing that, in light of recent events, may be grouped in three main categories: (1) climate change; (2) pandemic events; (3) intensification in migratory flows. All three of these aspects implicate a constant change of cities and affect the buildings that constitute them, to a greater or lesser extent, which must be able to react to such external stresses.

Recent events have shown how, for example, to respond to the issues caused by categories (2) and (3) it is necessary to provide for requests for temporary and/or long-term accommodation both through ad hoc structures of new construction and through the retrofit of the existing ones (most likely case in Italy). Requests that are not only purely constructive, but also concern the energy efficiency and environmental performance (in terms of sustainability and decarbonisation – compliance with the relatives Standards) of the structures and the control and maintenance of the indoor air quality characteristics (temperature, relative humidity, ventilation, filtration and air changes, salubrity and pleasantness).

From an engineering research point of view, category (1), i.e., that concerning climate change, certainly represents one of the major challenges on which most of the attention of the scientific community has been focused for over a decade. In particular, enhancing the urban resilience to extreme events, by making the city environment adapts to the new urban metabolism caused by the micro-climate changes (such as, the Urban Heat Island – UHI effect), seems to be a key point.

Mutations of the outdoor microclimatic features are in fact reflected in as many modifications of the indoor conditions, both in terms of engineering equipments (such as, increase in HVAC energy consumption) and air quality (e.g., worsening of the thermo-hygrometric characteristics). Outdoor and indoor characteristics that end up influencing each other incrementally: the increase in HVAC energy consumption leads to a greater release of heat into the outdoor environment which in turn (causing a rise of the temperature values) induces a further increase in the energy demand for the indoor climatization, hence contributing in worsening the UHI effect (with a retroactive effect).

Although the subject regarding the improvement of the environmental performance of building has been attentionated in over a decade of strategies and programmes, it has emerged that the building sector did not prove to necessarily have the prerogative of incrementally get better.

Hence, some aspects need to be further investigated in order to achieve a further improvement in both new and existing buildings, by promoting and supporting multidisciplinary knowledge and collaboration between different professional figures (such as, researchers, technicians, stakeholders and political decision makers), thus leading to solutions that are not only aimed at accomplishing energy efficiency, but also at enhancing the users' comfort, health and wellbeing inside and outside buildings, compatibly with the surrounding urban environment.

Figure B gives a visual representation of the energy consumption and energy-related CO_2 emissions breakdowns at global, European and national Italian levels.

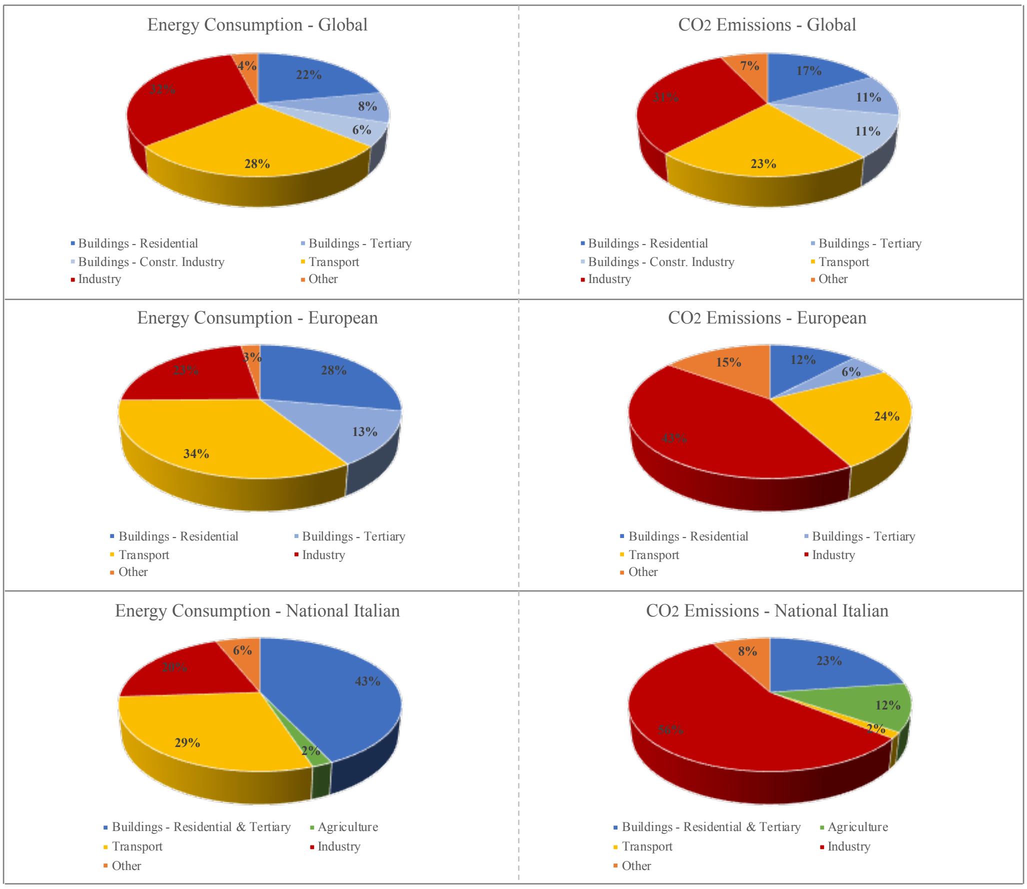


Figure B. Representation of the energy consumption and energy-related CO_2 emissions breakdowns at Global [2, 3], European [4, 5, 6] and National Italian [7, 8] levels.

According to the most recent data, energy consumption in the building sector is responsible for 36% of the energy use worldwide (corresponding to 39% of the total energy-related CO_2 emissions) [2, 3], while at the European level the building sector accounts for a share of the total energy consumption comprised between 25% and 40% (corresponding to about 35% of the overall CO_2 emissions throughout Europe) [4, 5, 6]. Concerning the Italian context, instead, such figures stand at about 40% and 17.5% for the energy consumption and for the CO_2 emissions, respectively. [7, 8].

For this reason, much attention has been paid, at global, European and single countries (national) levels on the important aspects regarding the reduction of energy consumption and the related decrease of greenhouse gases emissions in order to improve the environmental performance and the resilience of the building sector, both by the political and legislative bodies and by the scientific community.

From an institutional point of view, various strategies have been implemented.

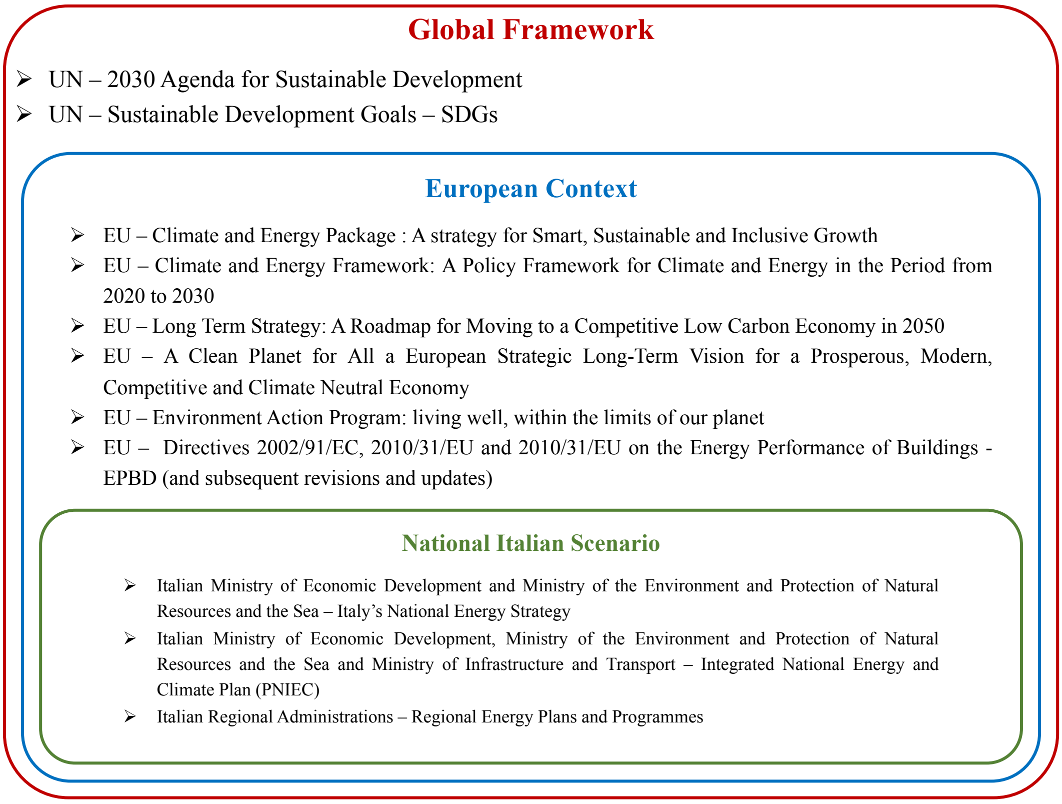
As a global framework, the UN 2030 Agenda for Sustainable Development [9], along with the 17 Sustainable Development Goals – SDGs (specifically Goal 11, 12 and 13, as shown in Figure C) [10], have to be quoted as reference initiatives.

Goal 11 – Make cities and human settlements inclusive, safe, resilient and sustainable [10], in particular, promotes buildings and cities that, other than being inclusive and safe, are also characterized by a more efficient use of resources (enhancing the use of renewable energy sources and reducing the employment of the traditional carbon-related ones) and by an abatement of the greenhouse gases emissions.

Figure C. UN Sustainable Development Goals (SDGs) [10], with those involing buildings (11, 12 and 13) circled in black.

Looking at the European context, the EU has been committed in implementing policies aimed at promoting a more sustainable and resilient society. Among these, the establishment of the ambitious goals for 2020 (“climate and energy package”) [11], 2030 (“climate and energy framework”) [12] and 2050 (“long-term strategy”) [13, 14] need to be mentioned. In addition, other important targets, aimed at decarbonizing and making more sustainable European cities, have been posed by the seventh Environment Action Program (EAP) [15]. And of course, within the European standards and regulations those specifically issued for building sector must be cited, namely the EPBD Directive and its recast [16, 17, 18], stating that new buildings built from 2021 ahead will have to be nearly zero-energy (NZE) buildings.

On national level, the most recent reference documents are represented by the Italy’s National Energy Strategy [19], the Integrated National Energy and Climate Plan – PNIEC [20] and the Annual Report on Energy Efficiency 2020 [7], which state the actions to put in place by 2030, in accordance with the long-term scenario drawn up in the EU Energy Roadmap 2050, aimed at achieving a reduction of the overall emissions of at least 80% compared to their respective 1990 levels, and where it is evident how a large part of such reductions can be obtained through interventions relating specifically to the building and the tertiary sectors.



Global Framework

- UN – 2030 Agenda for Sustainable Development
- UN – Sustainable Development Goals – SDGs

European Context

- EU – Climate and Energy Package : A strategy for Smart, Sustainable and Inclusive Growth
- EU – Climate and Energy Framework: A Policy Framework for Climate and Energy in the Period from 2020 to 2030
- EU – Long Term Strategy: A Roadmap for Moving to a Competitive Low Carbon Economy in 2050
- EU – A Clean Planet for All a European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy
- EU – Environment Action Program: living well, within the limits of our planet
- EU – Directives 2002/91/EC, 2010/31/EU and 2010/31/EU on the Energy Performance of Buildings - EPBD (and subsequent revisions and updates)

National Italian Scenario

- Italian Ministry of Economic Development and Ministry of the Environment and Protection of Natural Resources and the Sea – Italy’s National Energy Strategy
- Italian Ministry of Economic Development, Ministry of the Environment and Protection of Natural Resources and the Sea and Ministry of Infrastructure and Transport – Integrated National Energy and Climate Plan (PNIEC)
- Italian Regional Administrations – Regional Energy Plans and Programmes

Figure D. Summary scheme of the main strategies directed at improving the environmental performance and the resilience of buildings implemented at different levels.

To sum up what above discussed, Figure D gives a visual representation of the main strategies directed at improving the environmental performance and the resilience of buildings implemented at different levels.

Despite the effort spent in putting into effect the aforementioned actions, in recent years, the energy consumption in the building sector has experienced an increase, particularly in Italy [7]. That is why more exertion in advancing the current measures and finding new innovative strategies to improve energy efficiency and resilience of buildings are of paramount importance [21].

In light of the above presented framework and with the aim of bringing a contribution to the matter, the object of the research work carried out during the PhD course consisted in assessing strategies and solutions aimed at improving the energy efficiency, environmental performance and resilience of buildings, by means of both experimental and modelling approaches. For this purpose, a number of case studies were designed and conducted to estimate how the adoption of some proposed interventions could impact the energy consumption, the indoor comfort and contribute to the reduction of the CO_2 emissions of buildings.

Specifically, the experimental part of the work consisted in monitoring and measuring some characteristics, while the modelling part mainly involved the use and implementation of dynamic simulation mathematical models expressly intended for analysing and assessing the energy efficiency of buildings (through the use of the most popular suitable software, such as EnergyPlus, MATLAB and R Statistics).

Starting from a single building standpoint, a few solutions aimed at consuming less energy, in concomitance with guaranteeing indoor thermal (tempearature and relative humidity) and visual comfort (LED lighting) conditions for the occupants and improving the environmental performance, hence accomplishing a better mitigation and adaptation to the climate change, were proposed and analysed.

Other than making a more efficient use of traditional sources by improving energy savings, an important tool to improve buildings sustainability and resilience is represented by renewable energy sources – RES. In light of this, the photovoltaic-thermal systems (PV/T) have been object of part of the research activity, given their ability to produce electrical and thermal energy simultaneously.

A fundamental step when implementing measures and strategies for improving the environmental performance of buildings, is represented by the evaluation of their energy behavior; it is therefore important to have sound estimation methodologies. To this purpose, part of the work regarded an assessment of the evolution of the European Standards for the calculation of energy efficiency in buildings.

As a further research step, the spatial scale at which some of the proposed solutions can be applied was enlarged, passing from the single building point of view to that of a wider group of buildings, and how such condition may influence the energy efficiencies of the respective considered surrounding areas, by also taking into account the effect of the pertinent climatic conditions.

Moreover, a specific attention was given to two distinct types of buildings that represent an important reality in the Italian construction panorama, for both economic and historical reasons, namely tourism and historical buildings. Given their numerosity on the territory, such kind of buildings represent indeed a significant share of the energy consumers in the tertiary sector.

Below, a brief description of the content of each part of the dissertation is presented.

Part I – Interventions on Single Buildings

The first part of the dissertation is focused on measures, actions and considerations aimed at improving the environmental performance and resilience of single buildings and at the same time assuring the indoor thermal comfort, and it is divided into five sections: *Section I.A*, *Section I.B*, *Section I.C*, *Section I.D* and *Section I.E*.

- *Secion I.A* presents a series of solutions applied to the building envelope. Significant energy savings achievable in buildings can, indeed, be attributed to two main categories of components, namely technical plants and building envelope, having a synergistic relationship. In fact, while a reduction in energy consumption of technical plants consists in the use of active systems which entail further energy consumption, by acting on the building envelope, passive systems (not energy demanding) can be used, which allow to actually obtain a reduction of the energy consumption and simultaneously save on the use and the size of the techinical systems.

  Among the investigated solutions are new types of environment-friendly assemblies containing vegetal matter and ecological waste (solutions that have been spreading in recent years [22-26]), cool roof [27, 28] and green roof. The latter, in particular, having been gaining more attention lately due to their beneficial effects [29, 30], were analyzed more throughly for what concerns their thermophysical properties and thermal behaviour (also comparing different insulation materials adopted in their stratigraphy, either synthetic or natural), than regarding the environmental and economic aspects (by also making use of the Life Cycle Assessment – LCA instrument).
- *Section I.B* is based on the subject of LED (Light Emitting Diode) lighting technology, with particular reference to the relationship between the spectral distribution of power (SPD) and the effect that this exerts on the human body in terms of non-image-forming-reactions (NIF).

LED lighting represents, indeed, one of the most efficient solutions currently available to improve lighting energy efficiency and to reduce CO_2 emissions [31]. Nevertheless, another element to be analyzed further regarding the visual comfort (hence indoor comfort), is the so called NIF or "non-visual responses" to light. In fact, it has been shown how light, and its color in terms of SPD, have a strong impact on humans' health and wellbeing, affecting aspects that are not solely linked to vision, such as the perception of an environment, mood, and, more importantly the circadian system [32, 33, 34].

- *Section I.C* topic regards Renewable Energy Sources – RES, which appear to be a valid solution able to flank and/or, substitute fossil fuels, and it is actually being promoted by many countries'national energy strategies, including Italy [19]. At present, they are used to supply a small part of the world's total energy consumption; likely, however, their role is bound to increase because of the rise in fossil fuel prices, global warming and planetary pollution issues [35].

  This section is centered on the modelling of a particular kind of RES combined system, called solar photovoltaic thermal (PV/T) collector that is able to produce thermal and electrical energy simultaneously. Apart from the twofold energy performance, the advantage of the PV/T system consists in the reduction of the demand of physical space as compared to the separated photovoltaic (PV) and solar thermal (T) systems placed side-by-side. Such feature makes the systems particularly suitable for building rooftops installations, where the problem of limited usable shadow-free space constitutes a key issue [36, 37]. Accordingly, PV/T system can be considered a valid contribution to the implementation of the nearly Zero Energy Buildings (nZEB) concept [16, 17, 18].
- *Section I.D* concerns the definition of possible new easy and reliable indicators to achieve a synthetic quantitative judgement about the effectiveness of green roofs, by an environmental perspective, and also compared them to others building envelope technologies, and in different climate contexts. Specifically, in order to consider how the different weather conditions in which the buildings operate affect their performances [38, 39] the influence of diverse roof construction typologies on energy and indoor behaviours of buildings has been investigated in different geographical sites during both heating and cooling seasons.
- *Section I.E* reports an analysis relative to the evolution of the European Standards for energy efficiency in buildings. Such an analysis could also be helpful for both public administrations and professionals (designers,

researchers and technical experts) by providing some considerations regarding the reliability of the chosen calculation methodology to assess buildings' energy performance [40, 41, 42].

On purpose, the work involved a comparative between the in force EN ISO 13790 [43] and the recently issued EN ISO 52016 [44] Standards by means of the implementation of a methematical model aimed at the application of both the Standards to the same building, in order to compare the two approaches in relation to their different levels of complexity and to the levels of details of the results provided by them.

Part II – Interventions on Cluster of Buildings

In the second part of the dissertation the spatial scale at which the energy efficiency measures are applied has been expanded, moving from the single building point of view to a wider group of buildings, in order to also assess the cumulative effects of these solutions when simultaneously installed on multiple buildings on the surrounding areas; hence, with a view to the resilience of the urban environment [45, 46, 47].

Such analysis by cluster of buildings can also be useful in setting priorities for planning energy interventions, at different levels (municipal, regional, national, etc.). Political decision makers and stakeholders in drawing up energy plans need indeed effective data in order to purse their objective, which is to optimally allocate the available economic resources (and/or fundings) in order of planning and promoting energy efficiency measures in the building sector [42].

As representative of the definition of "cluster of buildings", it was decided to consider three typical urban contexts, that is a district of a metropolitan city and a small village (which were compared between them both in today's climate conditions and under future climate scenarios, and also in reference to different geographical contexts) and a university campus. University campuses (with their variety of buildings), in particular, have been increasingly gaining a lot of attention and concerns because they tend to spend a large share of the energy relative to the urban areas in which they are sited [48, 49, 50].

Part III – Tertiary Buildings: Historical and Tourism

The third part of the dissertation concentrates on two specific categories of buildings representative of the Italian cultural heritage, for historic as well as for economical reasons, i.e. historical and tourism buildings. Part III is divided into two sections: *Section III.A* and *Section III.B*.

- *Section III.A* deals with the theme of Indoor Air Quality – IAQ inside museums hosted by historical buildings, in terms of thermo-hygrometric conditions and aggressiveness of the microclimate inside the exhibition rooms. In such cases, in fact, the visitors' wellbeing, the preservation of the valuable works of art and the architectural integrity of the structure must be addressed; requirements that are often controversial [51-54]. On purpose, this Section proposes the implementation of a mathematical model to obtain a new risk index for works of art which, in addition to taking into account the microclimatic characteristics of the environment in question, is also inclusive of economic aspects.
- *Section III.B* investigates on the matter of energy effinciency in the tourism sector, which represent an important sector of the economic system, hence a relevant contributor to energy consumption, exerting a significant impact on the environment in terms of polluting emissions at global [55, 56], European [57] and national [58] levels. Thus, the availability of easy-to-apply tools for energy evaluating tourism facilities is of paramount importance for the orientation of this relevant sector towards a sustainable and resilient path.

  This Section presents a study concerning the assessment of the reduction of energy consumption achievable by agritourism buildings (significant share of the tourism sector in Italy), by means of a simple and reliable methodology based on the application of the EU Ecolabel Brand (European ecological quality mark) for tourist accommodation services [59] combined with the Italian ARERA (Italian Regulatory Authority for Energy Networks and Environment) computational methods [60] issued for the residential and tertiary building stock.

As previously mentioned, given the multidisciplinarity of the performed studies, and in order of rendering a picture as complete and precise as possible of the utilized methodological approaches and of the outcomes of the research work carried out during the PhD course, each chapter contained in the above introduced parts of the dissertation is represented by (and follows the typical format of) a published, under-review or recently submitted research journals and conference paper, in which all authors, including the undersigned PhD candidate, contributed equally to the design, experimental analyses and editing phases (conceptualization, data curation, methodology and writing).

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PART I – Interventions on Single Buildings

This part of the dissertation is focused on measures, actions and considerations aimed at improving the environmental performance and resilience of single buildings and at the same time assuring the indoor thermal comfort. It is divided into five sections:

- SECTION I.A – Building Envelope Components
- SECTION I.B – Lighting Systems: Energy and perception effects
- SECTION I.C – Renewable Energy Systems: The PV/T (photovoltaic-thermal) Case
- SECTION I.D – Sites' Climate Influence
- SECTION I.E – Ramblings on the Pertinent Standards

PART I – Interventions on Single Buildings

SECTION I.A – Building Envelope Components

This section deals with the subject of accomplishing buildings’ energy and climate sustainability by means of passive interventions concerning the building envelope components. Emphasis is placed, on particular, on the application of some actions dedicated to the enhancement of the roof characteristics in the aim of achieving both energy efficiency and the improvement of the indoor conditions. The thematic concerning the aspects related to the environmental sustainability of the proposed solutions, mainly in terms of life cycle assessment (LCA), will be also highlighted.
This section of the dissertation includes the following five chapters:

Chapter 1 - Retrofitting existing buildings by means of innovative envelope components: low-impacting new assemblies

Chapter 2 - On the hygrothermal behavior of coconuts fiber isulators on green roofs

Chapter 3 - Passive components for reducing environmental impacts of buildings: analysis of an experimental green roof

Chapter 4 - Covering the Gap for an Effective Energy and Environmental Design of green Roofs: Contributions from Experimental and Modelling Research

Chapter 5 - Green Roofs as Effective Tools for Improving the Indoor Comfort Levels of Buildings—An Application to a Case Study in Sicily

Chapter 1 - Retrofitting existing buildings by means of innovative envelope components: low-impacting new assemblies

This chapter consists in the following conference paper:
Cirrincione, L., La Gennusa, M., Marino, C., Nucara, A., Peri, G., Rizzo, G., Scaccianoce, G., Retrofitting existing buildings by means of innovative envelope components: Low-impacting new assemblies (2020), 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140532, pp. 500-505.
DOI: https://doi.org/10.1109/melecon48756.2020.9140532

Abstract: Current policies addressing the energy efficiency of buildings aimed at the control of their overall primary energy demand, require not only that the edifice envelope has to be properly designed to optimize its thermal performances, but also that the eco friendly properties of the involved building materials have to be properly taken into account, in order of assessing all the associated environmental costs. In fact, the design of envelope structures that are able to realize proper levels of thermal insulation and, in the same time, to employ materials characterized by low environmental impacts, are believed as the most effective strategies to be adopted in the aim of addressing the above-mentioned issues. In this regard natural materials, such as vegetal fibres or materials derived from the recycling of industrial/ agricultural waste, reveal very attractive characteristics. Indeed, recent studies on the use of natural materials in buildings concentrate on raw materials deriving from either agriculture, waste, or recycling processes. Such topics are the focuses of the present analysis. Specifically, this paper intends to provide a contribution in the field by identifying new types of environment-friendly composites, containing vegetal matters and ecological waste resulting from recycling activities. Outcomes of a series of performed laboratory analyses concerning the thermal conductivity of four different samples of assemblies, are quite promising and candidate these new composites – albeit further analyses are certainly recommended – as a practicable alternative to the mostly used traditional insulating materials.

Keywords: Thermal insulation; building envelope; waste materials; vegetal materials; thermal conductivity

1.1 Introduction

Worldwide, the construction of eco-compatible edifices is considered one of the pivotal solutions to reduce the pressure exerted by human activities on the environment and, hence, to contrast some causes of the climate change [1][2]. Two reasons can be posited here for this: firstly, the construction sector consumes a great amount of energy (in the EU, for example, buildings are responsible for 40% of the total final energy consumption and 36% of CO_2 emissions [3]); secondly, the management of buildings as well as their production have resulted to be a significant source of air pollutant emissions that Member States and technicians have to cope with [4][5][6], also preserving the world's resources [7][8]. However, buildings are subjected to a deep evolution of the related standards [9]. This is determined by the tentative of addressing buildings towards low-emissions paths by also guaranteeing them resilience features [10][11][12]. This vision is also recognized by many building certifications schemes such as, for instance, "BRE Environmental Assessment Method" (BREEAM) [13] and "Leadership in Environmental and Energy Design" (LEED) [14] which consider every construction as a compound system whose environmental sustainability has to be globally assessed [15]. Not by chance, a tentative is ongoing aimed at awarding buildings with excellence ecological brands [16] able to recognize their holistic performances. The building sector can be additionally assumed as the ideal platform where the main pillars of the "Industry 4.0" philosophy [17] can be implemented for minimizing the amount of virgin extracted materials, for recycling a large amount of the raw utilized ones and for addressing this sector toward a net-zero emissions features. In order of fulfilling these objectives, building materials should comply with several other requisites, such as: limiting the release in the air of toxic substances, and showing low contents of embodied energy [18]. Stimulated by the worldwide developing legislation in the matter of energy efficiency, researchers and the construction industry have mainly addressed the issue of thermal insulation properties of the building materials, fostering the development of innovative structures, which would allow both energy savings during the management phase of buildings and a proper level of indoor comfort quality [19][20][21], although within the limits imposed by the preservation of the planet's resources [22]. However, despite the improved level of the insulation features, the global environmental impact of building materials, which involves energy and resource use through the production cycle (although the rising recourse to recycling practices), emission of polluting agents is often remarkable [23][24] and depends on the manufacturing techniques and on climatic conditions of the site where they are used. On the contrary, if the above-described multifaceted perspective has to be adopted, the ecological properties of the building materials should be considered. In this regard, natural materials seem to properly contribute to reduce the pressure exerted by buildings on the natural environment through their whole cycle of life. The use of natural materials also involves the utilization of raw material resources, deriving from either agriculture [25][26][27] or waste or recycling processes [28][29]. The research in the field is also particularly concerned with the issues related to the Life Cycle Analysis (LCA) [30], including their costs [31].

This paper intends to propose a contribution in this field of research by reporting about an experimental analysis concerning new types of environment-friendly assemblies, containing vegetal matter and ecological waste, mainly coming from recycling practices. In more detail, the studied mixtures consist of a natural binder and a biocompatible material with different mass compositions. Specifically, the paper focuses on the thermal properties of these innovative composites and presents the results of a series of measurements of the thermal conductivity of four samples that were assembled by using dry vegetal matter or recycled items, which were all-grinded and blended in a paste of hydraulic lime (NHL 3.5) and water.

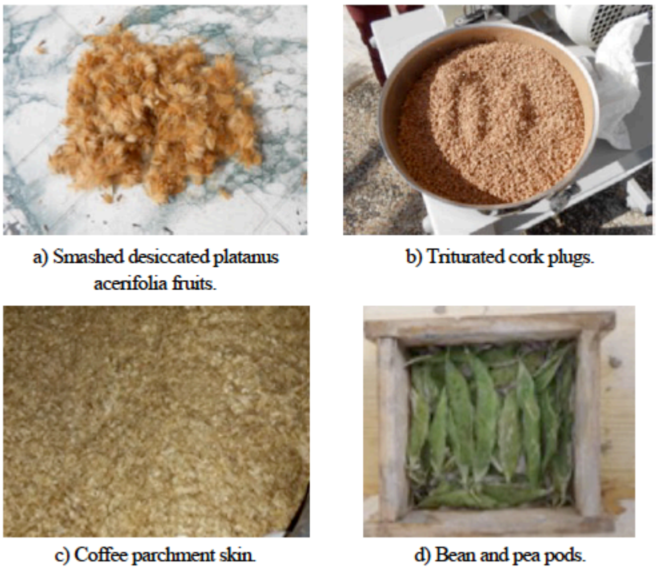
1.2 Materials and methods

1.2.A Selection of materials

This study is aimed at experimentally analysing the insulation characteristics of four new assemblies to be adopted as components of the building envelope. These structures are comprised of a paste of hydraulic lime and water, where different vegetal or recycled materials were properly blended, in order of conferring to the structure lightening features. The first phase of the present analysis concerns the selection of these components.

The binder used to realize the composite samples is hydraulic lime NHL 3.5. This material was selected thanks to its lower pressure exerted on the environment in comparison with the actually utilized cements and to the lower amount of energy involved in its working chain [32][33]. In addition, since its production process essentially relies on a heating of limestone, it can be considered at a large extent as a recyclable and biodegradable material. Moreover, the realization procedure is characterized by a carbon dioxide absorption: therefore, CO_2 releases during the manufacture of this product are partially balanced [34]. Apart its environmental performances, this type of binder shows interesting physical features that constitute a further advantage of the use of such components. Moreover, in addition to a relatively high comprehensive compression strength, NHL products are characterized by flexibility and breathability: therefore, the water entering the structure is easily expelled, in this way preventing an unwanted erosion of the materials, which is one of the main drawbacks of these kinds of materials, particularly when natural fibres are in contest.

As for the materials to be coupled with the binder, in the present application, natural fibres and waste deriving from agricultural processes or commercial and factory activities were selected - thanks to their widespread availability – for better addressing the environmental-related circular economy principles. With this aim, we have selected such materials in the attempt of proposing a second life to waste of agricultural processes that, at the moment, constitute a serious problem for farmers, not only by the environmental but also by the economic point of view. In other words, the utilization of these materials could turn a problem into an opportunity. Specifically, in order of realizing the new four assemblies here analysed, four different natural substances were used: desiccated and smashed platanus acerifolia fruits (Fig. 1.1a), triturated cork plugs (Fig. 1.1b), coffee parchment skin (Fig. 1.1c) and bean and pea pods (Fig. 1.1d). These materials can be easily and cheaply found on the local market since they are vegetable fibers deriving from very typically diffuse plants (i.e. platanus acerifolia fruits) and discarded materials from either commercial activities (cork plugs) or factories (coffee parchment skin) or farming (bean and pea pods).



a) Smashed desiccated platanus acerifolia fruits.

b) Triturated cork plugs.

c) Coffee parchment skin.

d) Bean and pea pods.

Figure 1.1. Natural and waste materials comprising the nine specimens.

1.2.B Preparation of specimens

All the above-mentioned matters were assembled to compose four specimens, which differ among them by the type of the used natural material, the mass fractions of the constituents and the total thickness of the assembly. All the materials, used as constituents of the samples, were preliminary treated to render them suitable for a homogenous blending with the paste of hydraulic lime and with water. In more details, the platanus acerifolia fruits were naturally desiccated and manually mashed

(Fig. 1.1a), the cork plugs were all triturated (Fig. 1.1b) to form particles having a diameter smaller than 2 mm. The bean and pea pods were naturally dried and cut into homogeneous pieces (Fig. 1.1d). The coffee parchment skin (Fig. 1.1c), which is the dried skin of the coffee bean - the husk that is removed during the roasting process - did not undergo any particular treatment because the material was sufficiently dry and had an already suitable structure. Using the wooden formworks illustrated in Fig. 1.2, four samples were realized, each of them indicated by means of a proper code (Table 1.1).

Figure 1.2. The parallelepiped wooden frame utilizes for shaping the samples.

Properly designed to comply with the requirements of the utilized measurement instruments for the measurement of their thermal properties, the plane dimensions of the parallelepiped items were 30 cm x 30 cm, with variable thickness, as indicated in Table 1.1.

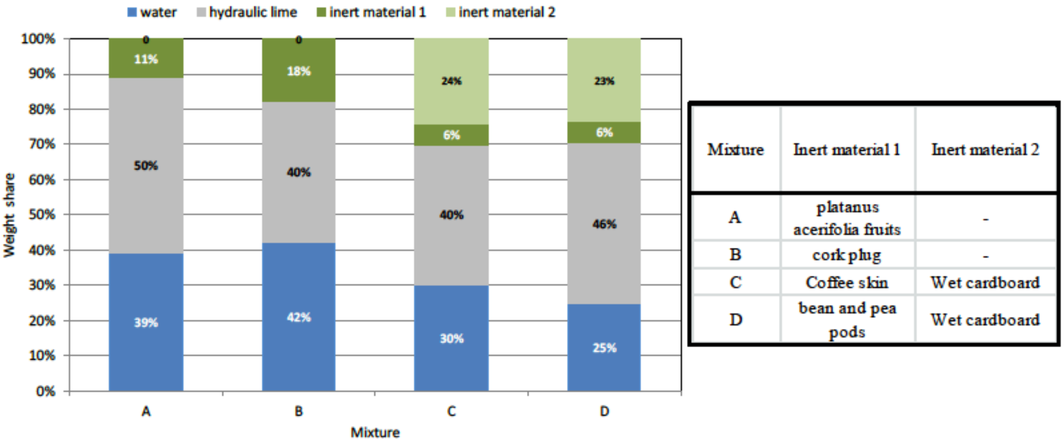
Table 1.1. Samples description with the proper identifying code.

Sample	Materials	Mixing material	Physical dimensions (cm)	
			Length x Width	Thickness
A	Platanus acerifolia fruits	-	30 x 30	4.6
B	Cork plug	-	30 x 30	2.9
C	Coffee skin	Wet cardboard	30 x 30	4
D	Bean and pea pods	Wet cardboard	30 x 30	4.9

All the specimens were constructed by blending a triturated, smashed or chopped organic/natural material with the hydraulic lime NHL 3.5, utilized as natural binder. Moreover, wet cardboard has been added to the samples C and D, as second inertial material. The composition of every single mixture is reported in Table 1.2, whereas Fig. 1.3 depicts the mass fractions of the various materials in each mixture.

Table 1.2. Mixtures' composition.

Sample	Weight (g)				
	Water	Hydraulic lime	Materials	Mixing material	Total
A	2140	2700	600	-	5440
B	810	766	340	-	1916
C	1500	1979	300	1200	4979
D	2025	3730	490	1910	6130



Mixture	Inert material 1	Inert material 2
A	platanus acerifolia fruits	-
B	cork plug	-
C	Coffee skin	Wet cardboard
D	bean and pea pods	Wet cardboard

Figure 1.3. Percentage by weight of the mixtures' compositions.

In order of achieving a suitable stability of the assembly and not to altering the homogeneity of the mixture with unwanted shifting of the materials, all the samples, once assembled, remained into the formworks for two days and, afterwards, were weighted for the first time. Subsequently, all the samples underwent a natural drying process. The graph reported in Fig. 1.4 shows the weight that was registered during this drying period, for each sample.

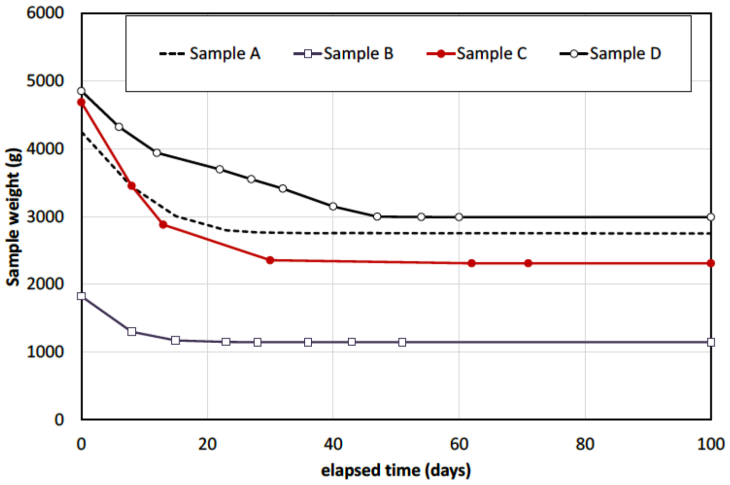


Figure 1.4. Sample weight trend.

High weight loss values within a period of 30 days may be observed for samples C and D, whose mixtures are characterized by the presence of comparable cardboard weight shares (24% and 23%, respectively). Between these last, lower weight losses were detected for the specimen D. Supposedly, this behaviour is due to the higher hydraulic lime content (between 37% and 46% of the total weight) and to the lower water content (between 25% and 27% of the total weight) of the mixture. In Fig. 1.5 the weight loss registered after 28 and 50 days from manufacturing is depicted.

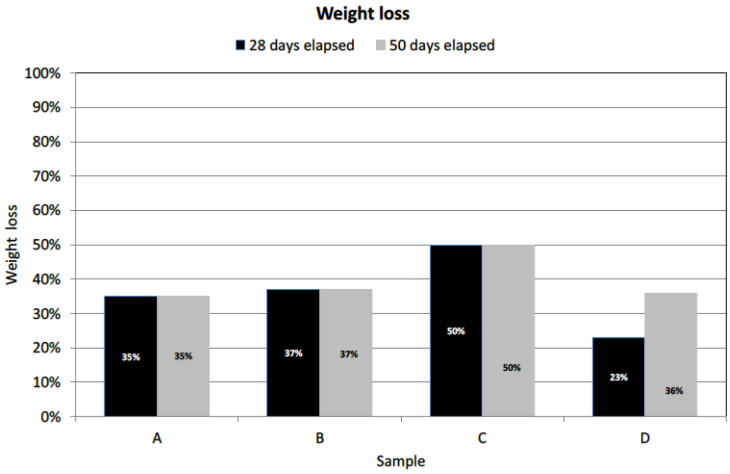
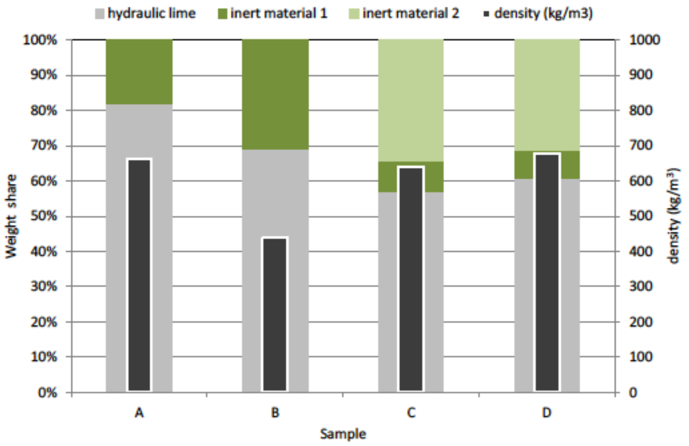


Figure 1.5. Percentages of the weight loss after 28 and 50 days from the sample manufacturing.

In conclusion, in Fig. 1.6 the density (kg/m^3) of the samples, at the end of the drying process, is reported. The figure also depicts the mass fractions of the various solid components of the mixture, with which each sample was manufactured. In this case, unlike in Fig. 1.3, the weight distribution was referred only to the solid components, and therefore the weight of the water was not considered.



Mixture	Inert material 1	Inert material 2
A	platanus acerifolia fruits	-
B	cork plug	-
C	Coffee skin	Wet cardboard
D	bean and pea pods	Wet cardboard

Figure 1.6. Density of the studied samples.

1.2.C Measurement procedure

Thermal tests have been performed on the prepared parallelepiped samples to investigate their thermal conductivity. In the present study a heat flow meter, which measures the steady heat transfer through flat materials according to ASTM Standard C518-17 [35] and EN 12667 [36], was used: the FOX 314TM heat flow mater (HFM) that is constituted by the proper measurement compartment and an external structure housing all the electronics with the control apparatus. The value of the thermal conductivity, *k*, is obtained by properly converting the value of the electric potential difference, through Eq. (1.1):

$$k = S_{cal}(t) \times Q \times \frac{\Delta_x}{\Delta_t} \tag{1.1}$$

where *Scal(t)* represents the calibration factor ($Wm^{-2}\ \mu V^{-1}$); *Q* is the value of the electric potential difference between the two transducers (μV); *Δx* is the sample thickness (m); *Δt* is the detected temperature difference between the two plates (°C).

1.3 Results and discussion

Thermal conductivity measure tests were performed at the end of the drying process, when the sample weight stabilized, that is, on average, after 40 days since the sample manufacturing. The results of this analysis are reported in Fig. 1.7, which depicts the variation of the measured thermal conductivity, *k*, with the temperature, for each studied sample.

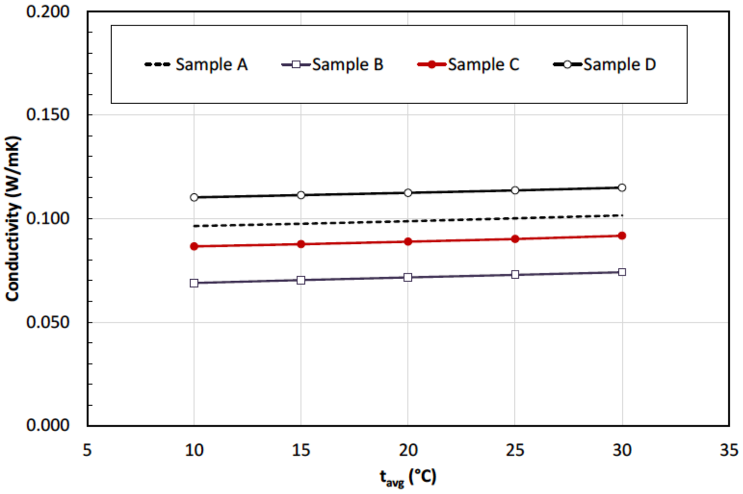


Figure 1.7. Measurement results.

It can be noted that, substantially confirming the outcomes of other studies [30][31], this variation is very small, so that an average value of the thermal conductivity can be used in the studied temperature range (0°C-40°C).

The mean and the standard deviation of the measured parameters are reported in Table 1.3. It is worthy of note that the lowest values of *k* correspond to samples B and C. Presumably, the performances of the two specimens are mostly due to the lightness and proper insulation properties of the inert material (grinded cork plug) in the case of the sample B, or to the low hydraulic lime content of sample C.

On the contrary, samples D showed the highest values of *k*. Probably, this behaviour is due to the structure of the specimen, where the inert material was coarsely crushed or cut in pieces and not finely grinded and blended into the paste. This fact could have created a more compact and less porous structure, which is responsible of the worse insulation performances of the samples.

Table 1.3. Measured thermal conductivity.

Sample	Average value, *k*	Stdandard Deviation
	($W\ m^{-1}\ K^{-1}$)	($W\ m^{-1}\ K^{-1}$)
A	0.0988	0.0018
B	0.0715	0.0018
C	0.089	0.0018
D	0.1125	0.0017

As a matter of fact, the results have proved that the specimens derived from homogeneous mixtures, where the inert natural material was finely grinded and blended into the paste of binder and water, show the most effective insulation features. Furthermore, the most fibrous vegetal materials seem to have better performance from this point of view.

On the other hand, other factors, which are strictly connected to each other, appear to affect the measured value of thermal conductivity: the hydraulic lime content and the final density reached by the sample after the drying process. Specifically, it has resulted that thermal conductivity tends to increase with the density of the sample, and, by and large, better performances, with lower thermal conductivity values, tend to characterize the samples with lower lime content.

As regards the effect of the temperature, the outcomes of the measures have proved that, if the thermal gradient across the slabs is maintained constant, thermal conductivity shows a reduced variability with the average temperature characterizing each test run. More precisely, it has been found that thermal conductivity tends to rise with temperature, but, on balance, the standard deviation of the measured parameter, in the studied temperature range (10°C÷30°C), is substantially low.

It is worth noting that the measured thermal conductivity values are lower than 0.15 W/(mK), confirming that, albeit further improvements are desirable, the studied composites can be considered a practicable alternative to the mostly used traditional insulating materials.

1.4 Conclusion

Nowadays, the construction of eco-compatible edifices, complying with requisites of overall environmental sustainability appears as one of the most feasible courses of action if the human impact on the environment has to be restrained in the years to come. Consequently, the demand for green building materials, not releasing toxic substances into the air, presenting both good thermo-physical properties and low-energy content, is sharply rising. In this context, natural materials are emerging because they are low cost, lightweight, and are more environmentally sustainable compared to traditional matters in composites used in buildings.

This study was aimed at analysing the insulation features of environment-friendly structures, composed by merging vegetal fibres or waste items, derived from farming or commercial/industrial processes, in a paste of hydraulic lime and water. Specifically, measures of the thermal conductivity of four different structures were performed using a heat flow meter apparatus. Apart from the type of material used as inert, the studied samples differ for the mass fractions of the various components and for the thickness of the assembly.

The samples have shown good insulation properties, although further analyses need to optimize the preparation process of the assemblies. Furthermore, containing waste materials, they might be a contribute to the recycling processes and can constitute one of the main ambits where the central pillars of Industry 4.0 concept can be realized in terms of minimal use of extracted raw material, energy efficiency and net-zero emissions.

On the other hand, although the encouraging results, in order to have a more comprehensive assessment of the innovative composites presented here, additional analyses should be carried out aimed at evaluating their mechanical resistance, the impact of moisture content and the influence of the drying process on their thermal and mechanical properties. In this direction further developments of the research activity have been planned.

Chapter 1 Acknowledgment

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Chapter 2 - On the hygrothermal behavior of coconuts fiber insulators on green roofs

This chapter consists in the following conference paper:
Fabbri, K., Tronchin, L., Barbieri, F., Merli, F., Manfren, M., Gennusa, M.L., Peri, G., Cirrincione, L., Panzera, M.F., On the hygrothermal behavior of coconuts fiber insulators on green roofs (2020) Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020, art. no. 9160779.
DOI: https://doi.org/10.1109/eeeic/icpseurope49358.2020.9160779

Abstract: Coconut fibre insulators, represent an insulating material considered as “exotic”, which clashes with the doubts of his thermo-hygrometric behavior, in particular, in the case of covering technology such as green roofs, a technological solution adopted in the case of sustainable buildings or nearly zero energy building. Green roofs represent a valid constructive solution with high thermal performances, adopted in existing and new buildings. The purpose of the research regards the study of the thermo-hygrometric behavior of the concrete and Cross-Laminated Timber (CLT) slabs, insulated with coconut fibre-boards (CF) such as alternative synthetic insulators, referred to 10 different green roofs scenarios. The results show that coconut fibre insulations are equally comparable to natural and synthetic materials, and their doubts for their applications, also in the green roofs, are related to technological solutions for the implementation in the market and their diffusion between the buildings materials.

Keywords: coconuts fibre, green roof, moisture, thermal insulation

2.1 Introduction

The green roof is a technology for the building's roofing that ensures high insulation and good thermal phase displacement. In the majority of the applications, the origin of the insulation materials adopted in the stratigraphy, are synthetic (e.g. EPS, etc.) or natural (e.g. wood fibre, wool glass, mineral wool, etc.). Between the natural fibres, several products use “exotic” natural materials such as corn cobs, sheep wool, etc... The coconut fibres, the object of this research, are natural fibres with tropical material. In recent years, several authors reported studies on green roofs, analysing the thermophysical properties and thermal behaviour of such insulators in different applications, considering buildings located in Europe, South America and in the Asian Countries, i.e. where the use of local materials is higher.

2.1.A Green Roofs

Several papers have dealt with application and evaluation of green roofs and its thermal performance in a) summer regime, b) winter regime, c) during the year. Tang and Zheng [1] in their research showed the dynamic properties of the roofs during the summer period, while He et al. [2] in their paper showed the temperature differences between the green building envelope and the same roof but in absence of the vegetation. Also, Cao et al. [3] analysed the temperature difference of green roofs between internal and external environments, based on plants type. On the other hand, Collins et al. [4] studied the thermal behaviour of the green roof in cold climatic conditions. In other papers, several authors studied the seasonal hygrothermal behaviour of green roof, considering different draining layers and characteristics of the roof, including thermophysical and hydraulic properties, like the papers of Vila et al [5] and Coma et al. [6]. In other papers, Almedia et al. [7] and Porcaro et. al [8], analysed the effect of the thermal performance of the filter layer (in the first case) and roofs with different substrates (in the second case), during summer and winter seasons. Moreover, other researchers have considered other variables. Squier and Davidson [9] have treated the variations in the thermal parameters of the layers and the roof during the winter and summer period. Ouldboukhitine and Belarbi [10] studied the variation of the thermal parameters of the green roofs with reference to hydraulic parameters based on plants evapotranspiration. Khotbehsara et al. [11], analysed different strategies for reducing heat loss throughout the year. Almost all the papers here reported have a common methodology: most of the authors considered the global thermal performances of the green roofs, without defining the thermal parameters for every single layer. It is remarkable the paper by Zirkelbach et al. [12], which defined the hygrothermal parameters for certain layers of the roof.

2.1.B Exotic thermal insulation materials

The term “exotic thermal insulation materials” refers to materials of various origins other than the normal material used for in-building insulation, such as bamboo fibres, wood fibres or paper from industrial wastes, date palm fibres, corn cob, ichu fibres, rice straw, etc. Nguyen et al. studied insulation materials in bamboo fibres, inserted in boards with bio-glues [13] and bio-binder [14], determining hygrothermal and mechanical parameters. Cetiner and Shea [15] focused exclusively on the hygrothermal and hydrothermal parameters to exploit the wood fibres from industrial wastes. Papadopulos [16], reported a comparison among thermophysical, acoustic, environmental and cost properties of materials of various nature. Other papers by several authors treated unconventional material that could be used in the building construction sector. For example, date palm fibres [17], corn cobs [18], natural ichu fibres [19], and rice straw [20]. In the latter example, the authors in addition to the thermal data reported also the mechanical properties. Wu et al. [21] reported experiments related to the mechanical and thermal properties of a hollow block made with wastes of several materials, whilst Faustino et al. [22] reported lab test for the use of insulators in corn cob and other materials such as kenaf, sheep wool etc., for flooring also to improve the soundproofing (i.e. reducing impact noise).

2.1.C Coconut fiber insulations and other utilizations

Among the natural materials, this article focuses on the “coconut fibre” which is utilised for different purposes: a) applied to boards without adding chemical binders or other natural fibre substances; b) applied to mixed boards having varying content coming from agricultural production wastes; c) added as a loose raw material introduced into building materials, d) aggregated to other substances used for different applications. As far as the research on boards with natural substances is related, Panyakaew and Fotios [23] studied the hygrothermal behaviour among CF boards and bagasse fibreboards (BF). Hirunlabh et al. [24] reported the thermophysical properties of CF boards and durian peel (DP) boards with chemical resins as additives. Khedari et al. [25] determined the same values testing mixed boards among CF and DP, calculating also hygrometric parameters. Among the various boards with mixed content, Fiorelli et al. [26] studied the thermo-hygrometric behaviour among multilayer boards with different content in CF and BF. Kimura et al. [27], determined thermal parameters of CF boards mixed with water and chemical substances at high temperatures. Other remarkable works about coconut fibres are reported in the papers of the following authors. Huan et al. [28] studied the thermal and acoustical behaviour and the fire resistance of composite boards mixed with CF by means of punching tests. Hassan et al. [29] made geopolymer foam based on CF’s ashes and other substances, defining thermophysical and mechanical characteristics. Madurwar et al. reported in review the thermophysical properties of the products based on CF derived from agricultural waste [30] whilst Schiavoni et al. added acoustical and mechanical properties of conventional and unconventional insulated materials available on the market [31]. Ramirez et al. studied the hygrothermal behaviour of ferrocement sandwich panels wall, insulated with CF, determining hygrothermal parameters [32] and subsequently thermodynamic parameters for the coconut ferrocement roofing system [33]. Iwaro et al. [34] related thermal performances of CF insulator with relative energy consumption, as well as Mintorogo et al. [35] reported cooling consumptions due to the use of concrete slab with and without CF insulation. The comparison between building elements was reported in Lertwattanaruk et al. [36], determining thermophysical and mechanical properties of the fibre cement slab with CF and palm oil fibres added. Rodrìguez et al. [37] studied the variation of temperature in the reinforced concrete slabs with the use of CF through lab tests. Other research related to CF, do not consider the thermophysical properties, but rather the mechanical properties structural buildings applications. For example, the paper by Ali et al. [38], Gunasekaran et al. [39] and Aldama et al [40]. Finally, Naranpanawe et al [41] and da Kumara et al. [42] described the electrochemical properties of CF oil compared with other oils, whilst Pedroso et al. [43] reported the CF's applications for the soundproofing. This literature overview aimed to determine the hygrothermal behaviour of green roofs with CF boards in the climatic zone "E", in order to compare those results with this work.

2.2 Goals

The purpose of this research is to determine the hygrothermal behaviour of green roofs equipped with insulation material made of coconut fibreboard and to compare the thermal performances with tables made on EPS, applied to a case study which considers two different types of structures: concrete slab floor (CLS) and CLT floor.

2.3 Methodology

The research is structured in the following steps:

- Definition of the reference scenarios for the simulations and relative thermophysical data of the materials;
- Software simulation;
- Restitution of results and interpretation.

2.3.A Scenarios

The scenarios here considered consist of two types of structures: Concrete CLS and Cross Laminated Timber (CLT, in Italian normally named as XLAM), with and without air gap (AG); each one with the same stratigraphy except for the insulation layer with different material and thickness. The simulated scenarios are reported in Table 2.1.

Table 2.1. Definition of the layer and thermophysical characteristics of the green roofs.

Slab	Air gap	Scenarios	Description
CLS	Without air gap	CLS 0	No Insulation
		CLS 1	Coconut fiber insulation Th: 8 cm
		CLS 2	Coconut fiber insulation Th: 12 cm
		CLS 3	Coconut fiber insulation Th: 16 cm
		CLS 4	EPS insulation Th: 8cm
	With air gap	CLS + AG 0	No Insulation
		CLS + AG 1	Coconut fiber insulation Th: 8 cm
		CLS + AG 2	Coconut fiber insulation Th: 12 cm
		CLS + AG 3	Coconut fiber insulation Th: 16 cm
		CLS + AG 4	EPS insulation Th: 8cm
CLT	Without air gap	CLT 0	No Insulation
		CLT 1	Coconut fiber insulation Th: 8 cm
		CLT 2	Coconut fiber insulation Th: 12 cm
		CLT 3	Coconut fiber insulation Th: 16 cm
		CLT 4	EPS insulation Th: 8cm
	With air gap	CLT + AG 0	No Insulation
		CLT + AG 1	Coconut fiber insulation Th: 8 cm
		CLT + AG 2	Coconut fiber insulation Th: 12 cm
		CLT + AG 3	Coconut fiber insulation Th: 16 cm
		CLT + AG 4	EPS insulation Th: 8cm

The base scenario provides a structure and stratigraphy of 40 cm. All the scenarios, including those of 70 cm thickness, are structurally correct; in other words, they could include very long flat roof for residential buildings. The thermophysical data of building materials are derived from the standard UNI 10351 [44], whilst the opaque ones from the standard UNI 10355. The thermophysical data of structures in CLT and coconut fibre boards are derived from the data sheets and increased by 20% accordingly to the standard UNI 10351.

2.3.B Thermophysical and hygrothermal simulation

The calculation of the thermophysical performances of the green roofs was carried out according to UNI EN ISO 6946 [45] for the thermal behaviour, ISO 13788 [46] for the hygrometric behaviour, and ISO 13786 [47] for the dynamic thermal behaviour. Calculations were carried out with Termolog Epix 10 [48] based on UNI 10349 for the climatic data of the zone “E” (degree days comprised between 2101 and 3000), and the UNI 11235 [49], for the realization of scenarios. Moreover, some other aspects related with economic aspects of energy enhancements or related factors [50] as multiscale analysis [51], confidence intervals [52], parametric assessment [53], and acoustic performance [54, 55] were considered but not reported in this paper.

2.4 Results and Discussion

2.4.A Interstitial condensation

The interstitial condensation depends on the stratigraphy and, in our case, the only element which varies among the scenarios is the insulation thickness in coconut fibre or EPS. Fig. 2.1 reports the relationship between insulation's permeability concerning that of the roof, and the internal moisture production rate (Gc). Interstitial condensation occurs in the roof with coconut fibre insulation CF (thickness from 12 to 16 cm), in absence of ventilation layer (CLS 2, 3 with values 0.0131 Kg/m^2 and 0.0220 Kg/m^2), and presence of this one (CLS + AG 2 and 3 with values 0.1134 Kg/m^2 and 0.0927 Kg/m^2). This is due to the high difference between the coefficient of vapour resistance (μ) of the various layers, related their thicknesses, causing condensation.

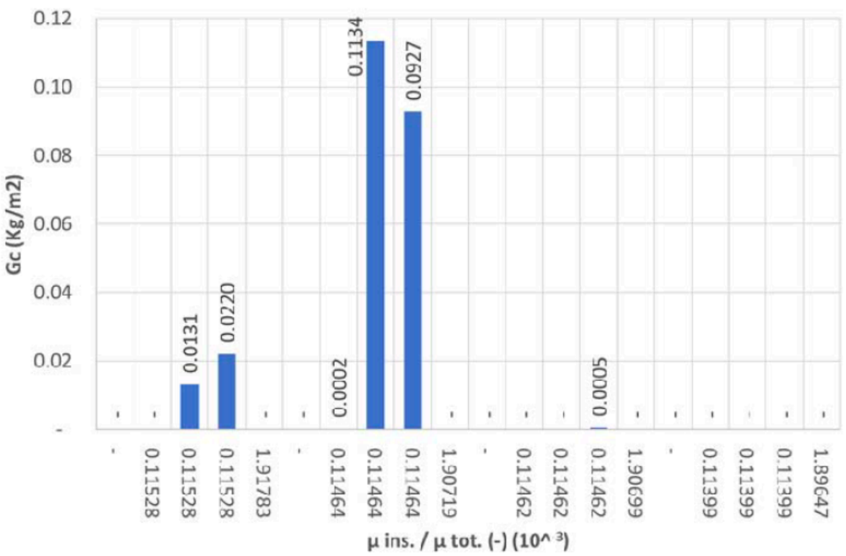

Figure 2.1. Hygrometric behaviour of the scenarios compared to the incidence of the material and the amount of vapour accumulated monthly.

2.4.B Thickness and transmittance

Another aspect is to evaluate whether there is a linear relationship between the stratigraphy's thickness of green roof and its transmittance U (W/m^{2}K). Fig. 2.2 shows that there isn't linearity between thickness and transmittance.

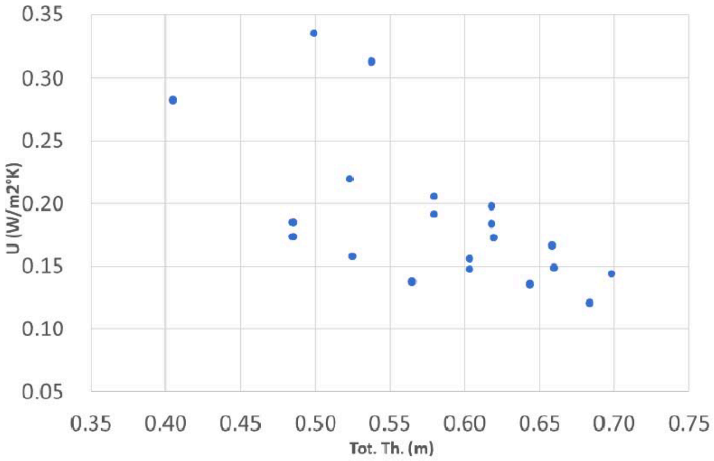

Figure 2.2. Trend's variation of thermal transmittance (U) in steady-state, compared to the increase of the total thickness (Tot. Th.) of the green roof: no correlation between parameters.

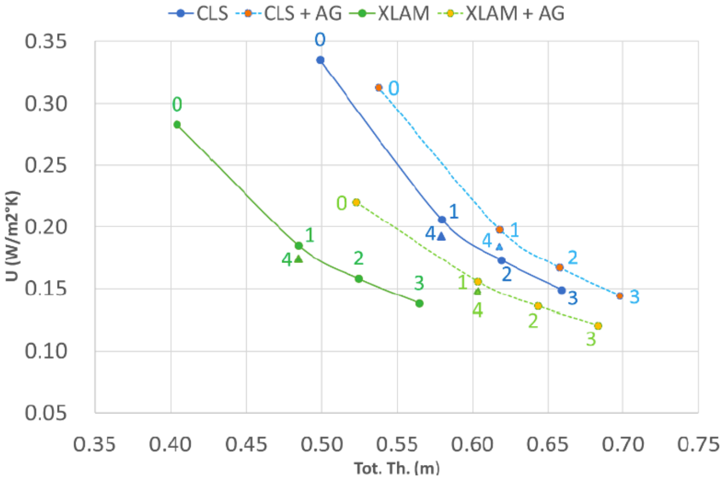

Figure 2.3. Trend's variation of thermal transmittance (U) in steady state, compared to the increase of the total thickness (Tot. Th.) of the green roof: correlation between parameters, thanks to a different bearing system.

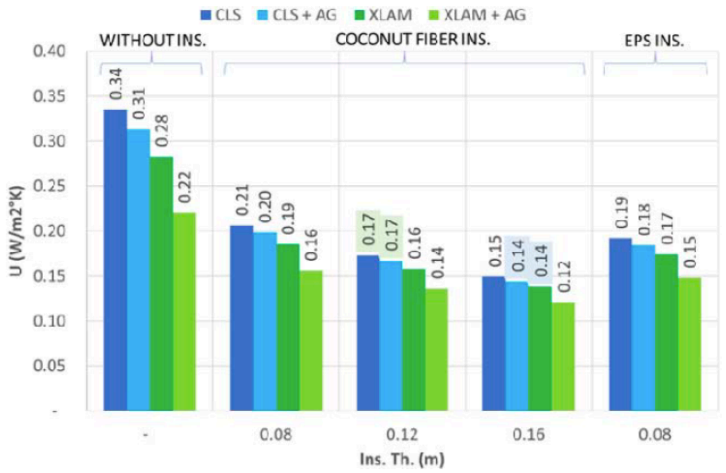

Figure 2.4. Thermal behaviour in steady-state (U) of the green roofs, compared to the presence/absence of the insulating material in addition to its thickness (Ins. Th.).

This correspondence occurs when analysing each green roof's structure. Fig. 2.3 shows that a linear relationship is found only for roofs belonging to the same constructive typology and the same insulation material. Looking more in detail Fig. 2.4, regarding coconut fibre insulation, it is possible to see that considering the same insulation thickness (12 cm and 16 cm), we have identical thermal performances between roofs having different stratigraphy (highlighted values). Furthermore, we have negligible transmittance differences, (roughly 0.01 W/m^{2}K) when we analyse all the green roofs with and without insulation layer (the difference is roughly 0.03 W/m^{2}K).

2.4.C Thermal behavior in dynamic system

Analysing the relationship between thermal periodic transmittance (Y) and insulation's thermal conductivity ($\lambda_{ins.}$) reported in Fig. 2.5, we found no significant differences between the performance of CF and EPS for all the roofs having the same thickness. Nevertheless, we found equal performances between CLS and CLT for roofs with and without the insulation layer.

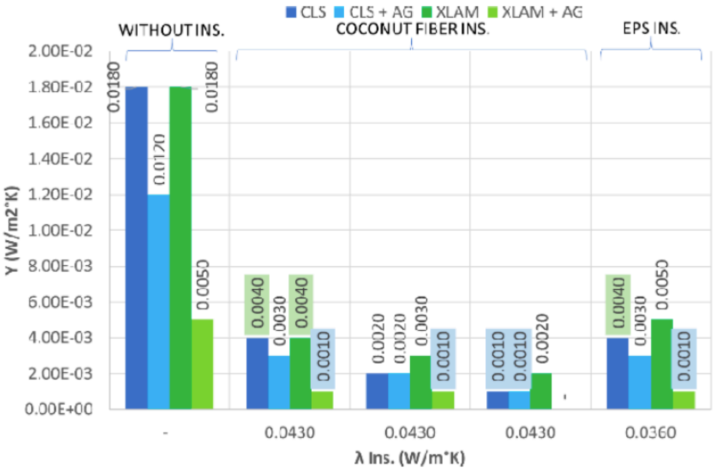

Figure 2.5. Thermal behaviour in dynamic conditions (Y) of the green roofs, compared to the presence/absence of the insulating material in addition to its thermal conductivity (λ_{ins}).

From this parameter, we calculated the thermal phase shift time. Comparing CF and EPS 8 cm thickness, we obtained the main value of the difference between the two materials of about 1 hour and 20 minutes. We could state that this delay might depend on both thickness and the thermophysical characteristics of each layer of the roof.

2.5 Conclusions

This research has applied the actual national and international standards to find useful results which could be applied in the field of building production, starting from the thermophysical parameters reported in the legislation. The results showed that CF and EPS reached the same thermohygrometric performance, as reported in scenario 3 (Fig. 2.5). This is an important result since CF represents a natural material whereas EPS is a synthetic one. Furthermore, considering the dynamic energy behaviour of both the different typologies of materials, the CF resulted in having a time shift 1 hour higher if compared to the synthetic insulator. However, there are some important constraints related to CF. First of all, CF is an “exotic” material, without any information (even not certified) about its thermohygrometric behaviour, even though its thermal performance is not worse than other synthetic material (as shown here and during the literature review). It is also worthy to underline that the same study would have been performed on other situation different from roofs (e.g., vertical walls); however, from the time shift perspective, the green roofs represent an important component of the building envelope, much more relevant than vertical walls. Finally, there is also another important component which is not considered in this work, which needs further and separate evaluation, i.e. the presence (or absence) of grass and other vegetal plants on the roof. So far, there is no specific and clear evaluation on this particular aspect and it deserves further and specific evaluation even by mean of experimental measuring campaign including in situ measurements, to determine its effect in energy behavior and performance, including its potential effectiveness.

Chapter 2 Acknowledgment

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Chapter 3 - Passive components for reducing environmental impacts of buildings: analysis of an experimental green roof

This chapter consists in the following conference paper:
Cirrincione, L., Gennusa, M.L., Marino, C., Nucara, A., Marvuglia, A., Peri, G. Passive components for reducing environmental impacts of buildings: analysis of an experimental green roof (2020) 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140546, pp. 494-499.
DOI: https://doi.org/10.1109/melecon48756.2020.9140546

Abstract: The reduction of the environmental impacts related to the building sector is a matter of outmost importance concerning the sustainable utilization of resources related to human activities. Such sector is in fact responsible for about 40% of both release of pollutants in the atmosphere and energy consumption. When trying to reduce buildings' environmental impacts, as well as to limit their energy consumption, building envelope passive systems can be used. Amongst these, green roofs have been gaining global attention due to their benefits in terms of resilience and sustainability, in order to mitigate the unfavourable urbanization effects. Research on the green roof has been indeed increasingly raising in recent years. Although the subject of green roofs has been dealt with extensively from many different points of view, there are currently some limits on which improvements can be made. In particular, the aim of the present work is to consider a somewhat overlooked aspect regarding green roofs, which is the overall energyenvironmental impact of such building component. The present work reports the results of a case study conducted on a Sicilian building sited in the Department of Engineering of the University of Palermo, where the Life Cycle Assessment (LCA) methodology has been applied.

Keywords: green roofs, buildings environmental impact, envelope passive components, life cycle assessment, energyenvironmental impact assessment.

3.1 Introduction

With the aim of pursuing a better environmental efficiency in human activities that would result in a more sustainable utilization of resources, the building sector plays a relevant role, being responsible for approximately 40% of both release of pollutants in the atmosphere [1, 2] and energy consumption for air-conditioning purposes [3, 4, 5]. In this perspective various strategies have been implemented [6, 7, 8, 9], and more effort in promoting actions and finding new approaches to reduce the environmental impacts related to the building sector has been put in the last few years [10, 11, 12, 13].

Specifically, the reduction of the energy consumption [8], along with the decrease of greenhouse gases emissions [14], represent the two most important aspects to which more attention has been paid.

When trying to reduce buildings' environmental impacts associated to climatization purposes two main categories of components can be considered, the technical plants and the building envelope, which are linked by a mutual synergistic relationship. In more detail, an impact reduction related to the technical plants consists in the use of more efficient active systems, which however entail an energy consumption, while for the building envelope, passive systems (no energy consuming) can be used. Such passive components allow to obtain a reduction of both the building's energy consumption (as well as a reduction of the size and the utilization time of the technical plants) and the whole environmental impact of the building.

Among passive solutions, green roofs have been gaining more attention lately [15, 16], not only because of their capacity to reduce the building's energy needs for air conditioning [17, 18], but also due to their ability of having a positive impact on the outdoor urban surroundings. In fact, various environmental benefits have been related to the use of green roofs, including reducing air pollution [19, 20], improving the management of runoff water [21, 22], mitigating noise [23], increasing the urban biodiversity [24] and alleviating the urban heat island (UHI) effects [25, 26]. Furthemore, they have been demonstrated to positively affect the indoor comfort levels of buildings [27].

Although the subject of green roofs has been dealt with extensively from many different points of view, both analytically and experimentally [28], some limitations [29, 30], on which further improvements can be made, have been evidenced: particularly, the role of the substrate in the whole environmental impact of this component, the effective analysis related to the cost of the disposal operations, and the current status of database of parameters required to model the radiative heat exchanges occurring in vegetation layer of these components. Moreover, in the opinion of the authors of the present paper, despite the wide diffusion of such technologies in urban contexts, the lack of an extensive knowledge of the environmental impact of the different life cycle phases of a green roof, and therefore of its overall environmental impact, seems to still exist.

On the basis of the above-made considerations, the present paper intends to provide a contribution to better assessing the Life Cycle Assessment (LCA) gaps related to the energy-environmental assessment of green roofs, by means of a case study conducted on a Sicilian building sited in the Department of Engineering of the University of Palermo.

3.2 The Case Study

In the presented case study the LCA methodology has been applied, in accordance with the ISO 14040 series standards [31, 32], to a green roof system, which has been installed on Building n.9 of the Department of Engineering of the University of Palermo (Figure 3.1). The analysis is aimed at evaluating the energy-environmental performance of such passive technology intended for the thermal insulation in winter season and the reduction of summer thermal loads.

Specifically, the objectives of the conducted analysis are the following:

- identifying the life cycle phases which are most responsible for the effects that this type of building coverage has on the considered environmental impact categories;
- assessing the influence that the components of the experimental system considered have on the green roof's production global impact.

3.2.A Green roof description by its main components

The analysed green roof system consists of eight sections positioned on three different zones of the roof of Building 9, in which different plant species have been installed, as reported in Figure 3.1 and Table 3.1.

(Zone A) (Zone B) (Zone C)

Figure 3.1. Green roof sections disposition on the building's roof.

Since the different sections differ only in the thickness of the cultivation substrate, as well as for the planted species, the LCA procedure has been applied to only one of the three zones, in particular to the C one (67 m^2 surface area), the results of which can be reasonably assumed to be representative of the potential impacts of the other two.

Table 3.1. Green Roof System Layout.

Zone	Section name	Plant species
A	A.1	*Phila nordiflora*
	A.2	*Phila nordiflora*
	A.3	*Gazania uniflora*
	A.4	*no vegetation*
B	B	*Gazania nivea*
C	C.1	*Sedum*
	C.2	*Mesembryanthemum barbatus*
	C.3	*Aptenia lancifolia*

In the following, the description of the commercially available technological package selected for the installation of the green roof pilot plant is reported, along with the relative section sketch represented in Figure 3.2. It is worth noting that no element with a specific anti-root function has been added to the system, due to the fact that the chosen waterproofing membrane element can also act as a protection against the roots action. The main components are the following:

- the selected waterproofing element, with an anti-root function, which is a prefabricated waterproof elastoplastomeric membrane, consisting of a compound (added with a product that acts as a chemical barrier against perforation by the roots) made of distilled bitumen modified with polypropylene containing a heavy "non-woven fabric" polyester reinforcement stabilized with longitudinal glass threads - Anti-root PE 4 mm©;
- the horizontal and vertical drainage elements, that consist of a polyethylene geonet hot-coupled with a filtering non-woven geotextile - Ecodren SD5©;
- the water storage element, constituted by expanded perlite mattresses - Igroperlite T2-5©;
- the filter element, made of a high tenacity non-woven geotextile felt, 100% calendered polypropylene - Drenalit F130-1.5©;
- the substrate, 5 cm thick, consisting in a mixture of peat, lapillus, pumice, expanded perlite Agrilit, bark, coconut fiber, special clays, soil improvers, organic fertilizers - Agriterram TV©.

Regarding the vegetation layer, taping and autochthonous plant species have been specifically selected due to their resistance to Mediterranean climates.

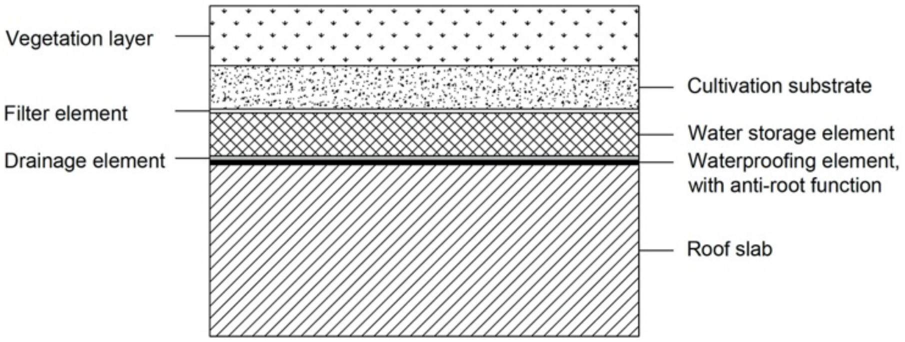

Figure 3.2. Section of the green roof object of the LCA analysis.

It should be pointed out that in the present case study, the LCA methodology was applied to all the elements mentioned above, except for the structural support (i.e. roof slab), the anti-root waterproofing membrane and the vegetation layer. This study is indeed intended to assessing the environmental impact that the layers added over the initial roof; especially the drainage, water storage, filter and substrate elements exert on the environment. However, the LCA of the structural support as well as that of the waterproofing membrane element do not represent a novelty and they are currently approached within the classical LCA of buildings. As regards vegetation, this component was not considered in the LCA analysis because of a lack of information.

Furthermore, although the roof is equipped with additional elements, necessary to ensure the correct operation and maintenance of the system itself (like the irrigation system, the downpipes and inspection walkways and wells), such accessory elements were not included in the LCA presented here.

3.3 Life Cycle Assessment of the Green Roof

The LCA has been conducted with the use of the SimaPro© software [33].

Both primary and secondary data were used in the study. The primary data come from: (i) on field observations related to the quantities of materials used to realise the individual layers of the roof; (ii) consultation of the technical data-sheets of the various components, made available by the supplier companies and/or traceable online; (iii) personal communications with both the suppliers of the elements and the staff who installed them. The secondary data, instead, were mainly taken from the Ecoinvent database [34] imported in the SimaPro© software.

3.3.A Functional unit and system boundaries

The functional unit (FU) chosen to conduct the assessment of the environmental performance of the green roof consists of 1 m^2 of green coverage; with respect to which the life cycle’s input and output flows of the system in question were assessed.

In particular, the life cycle phases taken into consideration to conduct the analysis, therefore the system boundaries, are: production, installation and maintenance.

It must be noted that the end-of-life phase, which includes the disposal of the green roof components and the related cost of transportation to the disposal site, is not part of the system's boundaries. This is essentially due to the lack of a precise information provided, for instance, by the technical sheets or by waste-related regulation on the most appropriate disposal/recycling processes of such materials, especially regarding the substrate.

In the following, the data that have been collected and the assumptions that have been made to model the previously mentioned three life cycle phases of the considered FU, (i.e. production, installation and maintenance) are reported.

3.3.A.1 Production

To model this phase, the processes related to the production of all the elements that constitute the FU were analysed, i.e. the supply of raw materials and the energy consumption related to the production processes. Finally, the effects of the transport phases necessary to transfer all the components from the place of production to the installation site were assessed.

Table 3.2 and Table 3.3 show the green roof elements and the materials making up each component, respectively.

Regarding the substrate, whose composition is indicated in Section 3.2.A, and in the absence of primary data, the following percentage weight distribution between inert and organic fractions, typical of such realizations, has been assumed:

- inert fraction equal to 86%;
- organic fraction equal to 14%.

In the absence of primary data regarding the specific fertilizer used in the substrate, a NPK slow release fertilizer with title 16-9-12, at 0.2% concentration (50 g/m^2 of vegetated surface), has been hypothesized as the amendment substance present in the mixture.

Since SimaPro© does not provide specific data on NPK fertilizers, it has been decided to model one of them using the individual components present in the database. Three different fertilizers were thus selected, based on their ability to supply nutrients (N, P, K). In more detail, nitric ammonium (457 g), triple superphosphate (187 g) and potassium sulfate (240 g) were selected. These quantities are able to provide the same dose of N, P and K that 1 kg of 16-9-12 NPK slow release fertilizer usually provides.

Table 3.2. Main components of Vegetated Zone C.

Components	**Selected commercial product**	**Quantity contained in the entire coverage (67 m^2)**
Substrate	AgriTERRAM TV©	1675 kg
Cloth with filtering function	Drenalit F130-1,5©	82 m^2
Water storage element	Igroperlite T2-5©	108 cushions
Drainage sheet	Ecodren SD5©	82 m^2

Table 3.3. Green Roof Main Materials and Components used for the Green Roof Production.

Green roof component		**Material**	**Overall quantity [kg]**	**Quantity contained in the FU [kg/m^2]**
Water storage element	Non-woven geotextile cushions, filled with expanded perlite	Perlite	1047	15.6
		Polyethylene terephthalate (cushion)	33	0.5
Filter element	Non-woven geotextile	Polypropylene	10.66	0.16
Drainage element	Geonet hot-coupled with a non-woven geotextile	High density polyethylene	36.9	0.55
		Polypropylene	9.84	0.15
Substrate	Inert and organic fractions blend	Lapillus, pumice, expanded perlite Agrilit, bark, coconut fiber, special clays, soil improvers, organic fertilizers.	1675	25

Concerning the transport distances, the information was obtained on the basis of communication with suppliers and with the aid of Google Earth. In this way it was possible to estimate for the substrate, the drainage component and the water storage element a distance between the production plant and the construction site of about 1050 km and 1500 km, respectively (considering only road transport). On the other hand, it was not possible to find data related to the location of the production plant of the filter element. Therefore, rather than assuming a distance's indicative value, which could have affected the results erroneously, it has been preferred not to consider such additional transport component in the analysis (Table 3.4).

Concerning data related to the transport of raw materials (polypropylene, high density polyethylene and polyethylene terephthalate) to the production plants of the green roof elements (namely drainage and water storage), in the absence of primary data, those present in the Ecoinvent database have been used (based on a European standard distance, which in turn relies on transport statistics).

Table 3.4. Distances Considered for the Materials Transport Analysis.

Green roof component	Route	Distance [km]	SimaPro$^{\copyright}$
Drainage element Water storage element	Lombardy – Sicily (road transport only)	1500	Transport, freight, lorry >32 ton, Euro4 (GLO)
Substrate	Lazio – Sicily (road transport only)	1050	

3.3.A.2 Installation

The installation process consisted in manually setting the various green roof layers.

It was decided to consider in the analysis the lift fuel consumption necessary to transfer the elements on the roof of the four storey Building n.9 and the water consumption needed for the planting and rooting of the selected plant species.

Specifically, to place the materials on the roof of Building n.9 a crane was used. Therefore, its fuel consumption per FU was estimated at 0.45 kg/m^2. While, the assessed water consumption per FU necessary for the planting and rooting of the plant species resulted being equal to 4.9 l/m^2.

3.3.A.3 Maintenance

The maintenance phase includes all those processes put in place in order to allow the correct operation of the green roof during its entire service life.

To model this phase, a lifespan of 40 years was assumed and only the fertilization activity was considered. In particular, it was hypothesized to fertilize the soil twice a year, as indicated in the Italian standard for the planning, installation, and maintenance of green roofs, namely the UNI 11235:2015 [35], in case of extensive green roofs (as this is the case) adding a total annual amount of NPK 16-9-12 fertilizer of 100 g/m^2.

The possibility of erosion and/or loss of material of the substrate (for instance, due to the effect of the wind), with the consequent refurbishment, or the consumption of water for irrigation have not been taken into consideration.

3.3.B Impact assessment methodology and impact categories considered

The assessment of the potential environmental impacts of the studied green roof was conducted using the CML-IA 2001 impact assessment method, which focuses on the following impact categories:

- Abiotic depletion (ADP)
- Climate change (global warming) (GWP 100a)
- Ozone layer depletion (ODP)
- Human toxicity (HTP)
- Ecotoxicity (terrestrial and aquatic):
- Fresh water aquatic ecotox. (FWEP)
- Marine aquatic ecotox. (MAEP)
- Terrestrial ecotox. (TEP)
- Photochemical oxidation (POCP)
- Acidification (AP)
- Eutrophication (EP)

3.4 Energy – Environmental Impact Assessment

This section contains the results of the performed LCA.

The following Table 3.5 reports the impacts of the considered life cycle phases for the selected impact categories mentioned above, while Table 3.6 summarizes the obtained results in percentage terms.

Table 3.5. Considered Life Cycle Phases' Environmental Impacts.

Impact category	Unit	Product.	Install.	Maint.	*Total*
ADP	kg Sb eq.	4.12E-05	9.46E-08	**1.00E-04**	*1.41E-04*
GWP 100a	kg CO_2 eq.	**3.38E+01**	1.70E-01	1.90E+01	*5.29E+01*
ODP	kg CFC-11 eq.	**2.54E-06**	7.19E-08	5.48E-07	*3.16E-06*
HTP	kg 1.4-DB eq.	**7.69E+00**	2.20E-02	4.56E+00	*1.23E+01*
FWEP	kg 1.4-DB eq.	**5.62E+00**	1.10E-02	3.11E+00	*8.74E+00*
MAEP	kg 1.4-DB eq.	**2.60E+04**	4.15E+01	1.46E+04	*4.07E+04*
TEP	kg 1.4-DB eq.	1.74E-02	6.58E-05	**3.36E-02**	*5.11E-02*
POCP	kg C_2H_4 eq.	**9.50E-03**	7.76E-05	3.30E-03	*1.29E-02*
AP	kg SO_2 eq.	**2.10E-01**	1.00E-03	1.00E-01	*3.11E-01*
EP	kg PO_4^{2-} eq.	**4.00E-02**	1.00E-04	3.40E-02	*7.41E-02*

Table 3.6. Life Cycle Phases' Percentages Impacts.

Impact category	Production	Installation	Maintenance
ADP	29.14%	0.07%	**70.80%**
GWP 100a	**63.86%**	0.32%	35.82%
ODP	**80.40%**	2.27%	17.32%
HTP	**62.66%**	0.18%	37.16%
FWEP	**64.29%**	0.13%	35.58%
MAEP	**63.97%**	0.10%	35.93%
TEP	34.07%	0.13%	**65.80%**
POCP	**73.77%**	0.60%	25.63%
AP	**67.52%**	0.32%	32.15%
EP	**53.98%**	0.13%	45.88%

The numerical results reported in Table 3.5 show how, except for the abiotic depletion (ADP) and the terrestrial ecotoxicity (TEP), the phase which weighs more on the life cycle analysis is the production one, as better highlighted in Table 3.6, where the results in terms of percentages have been reported. The installation phase, instead, seems to be almost irrelevant.

Therefore, since in the present analysis the production phase turned out to be the most relevant, it has been decided to also calculate the potential impacts of the individual components on the production total impact. Table 3.7 and Table 3.8 report the obtained numerical values and the individual components' percentages breakdown, respectively.

Table 3.7. Potential Impacts of the Individual Components on the Production Total Impact.

Imp. cat.	Unit	Subst.	Filtr.	Water stor.	Drain.	*Total*
ADP	kg Sb eq.	1.09E-05	7.51E-07	**2.58E-05**	3.65E-06	*4.12E-05*
GWP 100a	kg CO_2 eq.	3.25E+00	1.03E+00	**2.49E+01**	4.59E+00	*3.38E+01*
ODP	kg CFC-11 eq.	2.23E-07	3.77E-08	**2.11E-06**	1.73E-07	*2.54E-06*
HTP	kg 1.4-DB eq.	5.70E-01	2.20E-01	**5.90E+00**	1.00E+00	*7.69E+00*
FWEP	kg 1.4-DB eq.	4.50E-01	2.00E-01	**4.10E+00**	8.70E-01	*5.62E+00*
MAEP	kg 1.4-DB eq.	1.38E+03	8.45E+02	**2.01E+04**	3.74E+03	*2.60E+04*
TEP	kg 1.4-DB eq.	1.30E-03	9.00E-04	**1.10E-02**	4.10E-03	*1.73E-02*
POCP	kg C_2H_4 eq.	5.00E-04	3.00E-04	**7.00E-03**	1.00E-03	*8.80E-03*
AP	kg SO_2 eq.	1.40E-02	5.00E-03	**1.70E-01**	2.40E-02	*2.13E-01*
EP	kg PO_4^{2-} eq.	4.00E-03	1.00E-03	**3.00E-02**	5.60E-03	*4.06E-02*

Table 3.8. Percentage Potential Environmental Impacts of the Individual Components on the Production Total Impact.

Impact category	Substrate	Filtr.	Water storage	Drainage
ADP	26.55%	1.83%	**62.76%**	8.86%
GWP 100a	9.62%	3.05%	**73.75%**	13.58%
ODP	8.75%	1.48%	**82.99%**	6.78%
HTP	7.41%	2.86%	**76.72%**	13.00%
FWEP	8.01%	3.56%	**72.95%**	15.48%
MAEP	5.29%	3.25%	**77.10%**	14.36%
TEP	7.51%	5.20%	**63.58%**	23.70%
POCP	5.68%	3.41%	**79.55%**	11.36%
AP	6.57%	2.35%	**79.81%**	11.27%
EP	9.85%	2.46%	**73.89%**	13.79%

Looking at the outcomes, it can be noticed how the water storage element represents the predominant component, followed by the drainage element, the substrate and finally the filter element.

The results reported in Table 3.5, 3.6, 3.7 and 3.8 appear to be in reasonable agreement with both literature data [36, 37, 38] and previous analyses performed by the authors [29], demonstrating that for all the considered green roof elements the highest environmental impacts come from the production phase.

Naturally, the outcomes relative to each individual impact category should be investigated more in detail since they are strongly affected by the materials used; as demonstrated by the abiotic depletion category-obtained values which resulted higher than usual (most probably due to the use of significant quantities of perlite in the considered configuration); while the other data, as previously mentioned, are mostly in agreement with previous studies present in literature.

3.5 Conclusion

The idea behind the presented work derived from considerations regarding the lack of energy-environmental impact analyses of green roofs from a Life Cycle Assessment perspective. In this respect, with the aim of bringing a contribution in overcoming such current LCA gap and because of the increasing diffusion of such technologies in urban contexts, a case study involving an experimental green roof installed on a Sicilian building sited in the Department of Engineering of the University of Palermo, has been conducted. In particular, the impact evaluation of the green roof was performed by taking into account three phases: production, installation and maintenance. The results of the assessment confirmed, as expected, that in the considered context the highest environmental impacts are attributable to the production phase.

Furthermore, it must be noted that the end-of-life phase of the green roof, which has not been accounted for here due to the lack of precise information available (e.g. in the technical sheets of the components or the waste regulation on the most appropriate disposal/recycling processes of such materials, especially for the substrate) is currently being investigated by the authors as further advancement in the analysis. A more indepth and comprehensive analysis should, in fact, also take into consideration the disposal of the green roof components and the related cost of transportation to the disposal site.

In conclusion, although green roofs have been gaining global attention in the last few years, due to their multiple energy, environmental and social benefits, there are still several research areas and technical difficulties that need to be addressed, such as the evaluation of the initial high construction and maintenance costs, or the consideration of possible roof leakage problems and their proper economical evaluation.

Chapter 3 Acknowledgment

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Chapter 4 - Covering the Gap for an Effective Energy and Environmental Design of Green Roofs: Contributions from Experimental and Modelling Researches

This chapter consists in the following book chapter:
Laura Cirrincione, Giorgia Peri, Covering the Gap for an Effective Energy and Environmental Design of Green Roofs: Contributions from Experimental and Modelling Researches (2020), “Rethinking sustainability towards a regenerative economy”, Andreucci, M.B., Marvuglia, A., Baltov, M., Hansen, P., Reith, A., (eds.), Springer, ISBN: 978-3-030-71818-3, *IN PRESS.*

Abstract: Green roofs are components of the building envelope that have become increasingly popular in urban contexts because other than providing numerous environmental benefits are also capable to reduce building energy consumption especially in summer. However, despite all these advantages, green roofs are still affected by some limits. Specifically, there are some gaps affecting the energy modelling consisting in the absence of a proper database containing information (growth stage, leaf area index and coverage ratio) relative to the different green roof plant species, which technicians could use in case of lacking of actual field data to perform energy analysis of buildings equipped with green roofs. These gaps concern also environmental and economic assessments of such technology. In fact, the currently available green roof LCA and LCC studies seem to underestimate the role of the substrate on the overall environmental impact and the role of the disposal phase on the life cycle cost of the green roof. In this chapter all these aspects are addressed, and contributions to their solution, which arose from both experimental and modelling research carried out by the authors are presented.

Keywords: Green Roofs; LCA; Radiative Heat Exchanges; Energy Analysis; Environmental Analysis.

4.1 Introduction

Green roofs represent an increasingly important building passive component in urban contexts due to the many benefits that can be attributed to them. Green roofs allow indeed to reduce the air pollution (Zhang, 2015; Abhijith, 2017), mitigate noise (Timothy Van Renterghem, 2018; Liu C., 2018), improve the management of runoff water (Soulis, 2017; Vijayaraghavan, 2019), increase the urban biodiversity (Köhler, 2018; Francis, 2017), and ease the Urban Heat Island (UHI) effects (Yang, 2018;

Peri, 2013; Bevilacqua, 2017; Solcerova, 2017). As regards this latter, a possible reduction of the average ambient temperature ranging between 0.3 and 3 K has been indicated for vegetated roofs, when deployed on a city scale, thanks to the evapotranspiration effect (Santamouris, 2014). A review of all the advantages provided by green roofs is presented in (Shafique, 2018).

Apart from the above-cited several environmental benefits, vegetated roofs have also become increasingly appealing as a technological option due to their capacity in decreasing the buildings' climatization energy consumption and at the same time improving the indoor thermal comfort levels (Cirrincione, 2020). Their suitability in improving the energy performance of buildings equipped with them has largely been addressed in literature over the recent years. Based on a literature review we conducted previously (La Gennusa, 2019), it arises that:

1) there is a wide agreement among scientists on the fact that during the summer period the presence of green roofs provides a thermal protection for the building (Niachou, 2001);
2) on the contrary, the performance of vegetated roofs in winter is somewhat a controversial issue; in fact, green roofs mostly reduce the total heating load (Silva, 2016), but in some cases they do not produce any advantage or even cause slightly adverse conditions (Santamouris, 2007; Jaffal, 2012);
3) vegetated roofs have mostly a positive impact on the total energy consumption of buildings (Niachou, 2001; Santamouris, 2007; Jaffal, 2012) implying a net reduction of the total annual energy demand compared to traditional roofs.

The reasons of such behaviour can be traced in some characteristics of this type of roof that have an influence on green roof thermal and energy performance. Specifically, factors that contribute to reduce the energy demand for cooling purposes. Thus, the above-mentioned positive effect can be summarized as follows:

1) direct shading of the roof by the vegetation;
2) cooling of the air surrounding the roof due to the evapotranspiration process;
3) higher value of the roof albedo (typical values range from 0.7 to 0.85 (Saadatian, 2013)).

While, items that contribute to reduce the energy demand for heating purposes can be summarized as follows:

1) additional insulation layer provided by the technological system "green roof" added to the roof;
2) lower thermal convention on the external surface due to the presence of the vegetation.

Nonetheless, some circumstances that may increase the heat losses, rather than decreasing them, may occur. Among these, the climatic conditions and especially the precipitation regime of the site where the green roof is located, which have an influence on the effect provided by green roofs in winter, and particularly their additional insulation level which modifies the soil humidity content and in turn the soil thermal conductivity.

Despite all the so far mentioned numerous important benefits related to the use of green roofs as building envelope component, there are currently some modelling gaps increasing the time required for their design phases, on which improvements can be made; these gaps concern both environmental and economic aspects. Hereafter we address the points mentioned above and list some contributions to their solution, particularly referred to extensive green roofs, that arose from both our experimental and modelling research.

4.2 An Insight on the Energy Modelling of Green Roofs and on Some of its Currents Gaps

As far as the modelling of green roofs is concerned, it should be noted that the high complexity characterizing the heat transfer occurring in a green roof, especially due to the presence of the vegetation and substrate, makes it complicated to implement a detailed model (Del Barrio, 1998). Therefore, it becomes necessary to assume simplifying hypotheses. Among these hypotheses, one is related to the behaviour of the canopy layer and it consists in approaching the vegetation layer through the so-called “big-leaf approach”, which is typically used to assess the solar absorption attributable to the green roof canopies (Monteith, 1965; De Pury, 1997).

In order of properly modelling the energy performance of buildings provided with green roofs (considered ad passive components), some reliable, yet simplified, mathematical procedures have been implemented and are available in literature. An extensive review of them is well presented in (Quezada-García, 2020). Among these, the one developed by Sailor (Sailor, 2008) has also been implemented in one of the most widely used building energy simulation software, i.e. EnergyPlus (EnergyPlus). Table 4.1 lists the typical input parameters requested by this simulation tool for calculating the different heat transfer components of the energy balance of a green roof and thus its contribution to the energy consumption of building. As it can be observed, green-roof-related input data are essentially related to vegetation and soil layers.

Table 4.1. Main input parameters required by EnergyPlus to calculate the effect of a green roof on the energy consumption of a building equipped with it (Peri, 2016).

Green roof's layer	Parameter	Parameter's unit	Parameter's description
Canopy	Leaf reflectance	(-)	It measures the percentage of incident solar radiation reflected by the leaf.
	Leaf emissivity	(-)	It is the ratio between the thermal radiation emitted by the leaf and that emitted by a black body at the same temperature.
	Leaf area index (LAI)	(-)	It measures the vegetation density.
	Height of the plants	(m)	It represents the average height of vegetable species.
	Minimum stomatal resistance	(s/m)	It measures the resistance offered to vapour diffusion from the pores on the plant leaves.
	Roughness class	Smooth/ Medium/ Rough	It gives an indication on the surface texture of the leaves.
Substrate	Soil thickness	(m)	It is a geometrical property of the soil.
	Conductivity of dry soil	(W/(mK))	It indicates the substrate's capability to transfer heat by conduction.
	Density of dry soil	(kg/m^3)	It indicates the mass of dry soil that occupies a unitary volume.
	Specific heat dry soil	(J/(kg K)).	It indicates the amount of heat needed to provide to the unitary mass of dry soil to increase its temperature of 1 degree.
	Thermal absorptance	(-)	It measures the percentage of radiation absorbed by the soil in the infrared, ultraviolet and visible range of the electromagnetic spectrum.
	Solar absorptance	(-)	
	Visible absorptance	(-)	
	Saturation Volumetric Moisture Content of the soil layer	(-)	It represents the maximum volumetric water content that the substrate can store.
	Residual volumetric moisture content of the soil layer	(-)	It indicates the minimum possible volumetric water content that a soil can undertake after a drying process.

4.2.1 Radiative Inter-canopies Heat Exchanges: the Lack of a Proper database of Pertinent Physical Parameters

Relatively to the energy issues, one of the biggest limitations is represented by the lack of knowledge of the mechanisms and physical parameters that govern radiative exchanges between the plants and the external environment and between the plant essences themselves ("intercanopies heat exchanges").

Based on a literature review carried out by the authors, aimed at investigating the availability and typology of some parameters related to vegetation and soil (i.e. experimental or analytical data, obtained both from experimental applications and theoretical data on plant canopies, plant species and growth stage which the available data are referred to) (Peri, 2016), it has emerged the absence of a proper database containing information (growth stage, leaf area index and coverage ratio) for different green roof plant species, which technicians could utilize in the eventuality of a lack of specific field data. This circumstance has been found especially in the case of shortwave radiation exchange inside the green roof canopy layer, which is a component of the green roofs' energy balance that, as demonstrated by Feng et al. in their work (Feng, 2010), plays an important role in the green roofs' energy balance. More specifically, it has been noticed that the current database containing the required data parameters to model this component of the radiative exchanges occurring within green roofs' canopies has some inherent limitations:

- is so far quite limited because it is referred only to a few plant species;
- almost all investigated parameters range of values are usually rather large (e.g. LAI values found range from 1 to 5), which could make even more challenging the choice of the values most appropriate for each of the models;
- (existing databases) do not fit this kind of roof peculiarities, represented by the fact that such component consists of living elements (i.e. vegetation) that grow and/or decay with time, modifying important parameters involved in the modelling of the green roof, such as the (LAI) and the coverage ratio (Santamouris, 2007; Peri, 2016; La Gennusa, 2018). Changes in such variables, which obviously influence the building energy savings related to green roofs (Silva, 2016; Zinzi, 2012), have been found to be frequently simplified instead, meaning that the available values in literature concern specific growth levels of specific plant species.

Therefore, in our opinion, the absence of a proper database appears of no negligible importance because a technician, who is tasked to assess the green roof impact on the energy consumption of a building equipped with it, might be forced to refer to common values, which do not represent the specific vegetated implantation; this circumstance may imply a simulation scenario not comparable with the actual one, that might lead to an inaccurate assessment of the buildings' thermal loads (heating and cooling).

In this respect, we have performed an evaluation of the buildings' energy estimation errors that might occur when using generic values for the green roofs' vegetation parameters. The outcomes of such estimation were compared to the results obtained from experimental data, deriving from a monitoring campaign (conducted by the authors) that is described in the following (paragraph 5.2.2).

In detail, the building yearly energy needs, both as summation of heating and cooling then separately, have been calculated, hypothesizing four different scenarios relative to the vegetation parameters to give as input to the utilised software (DesignBuilder©). In particular, the four considered parameters set of values were the following:

- field monitored data;
- fixed minimum values;
- maximum values;
- average values.

The simulations outcomes, listed in Table 4.2, put in light the need of improving the database with data specific for the typology of installed green roof, in order to render the building energy performance simulations more reliable. In fact, as it can be observed from the results, significant errors (up to 45% for heating) in the estimation of thermal loads might be related to the use of generic data.

Table 4.2. Potential errors due to the use generic vegetation data (Peri, 2016).

Set of data assigned to the vegetation parameters	**Ranges of errors potentially occurring**		
	Cooling	*Heating*	*Annual (heating + cooling)*
Minimum values	10% and 24%,	14%and 33%,	8% and 17%,
Maximum values	4% and 14%,	12% and 45%,	2% and 10%
Average values	1% and 9%.	7% and 19%.	1.5% and 7%

4.2.2 An Experimental-side Contribution Towards More Reliable Energy Performance Simulations of Buildings with Green Roofs

In order to contribute to populate the database of parameters related to the vegetation layer of extensive green roofs, required by the current calculation tools to assess the effect of a specific green roof on the energy consumption of a building, we decided to experimentally measure three important physical parameters governing the green roofs energy performance:

- coverage ratio (σ_f),
- leaf area index (LAI)
- foliage temperature (Tf).

The choice of these three parameters relies on the fact that the LAI provides information on the depth that the solar radiation has to go through before reaching the roof (indicating the level of its attenuation by the vegetation), while the coverage ratio, σ_f, identifies parts of the roofs directly hit by the solar radiation, which are then characterized by a different energy balance. We measured the growth-related parameters of these two plants according to technical protocols that refer to techniques widely diffused in the agrarian field. On the other hand, the foliage temperature T_f is clearly an important parameter of the vegetation's energy balance and in turn of the green roof's energy balance.

Six plant species were experimentally investigated with reference to different growth levels in the same lapse of time: *Phyla nordiflora*, *Aptenia lancifolia*, *Mesembryanthenum barbatus*, *Gazania nivea*, *Gazania uniflora*, and *Sedum* (Figure 4.1). These vegetable species are planted into three plots of extensive green coverings, which are sited in the *campus* of the University of Palermo.

A simple optical procedure was used to obtain the coverage ratio (Walter, 2015), based on a pixel-counting procedure applied to some green roof squares digital pictures (to this aim, wooden squares were built ad-hoc).

As regards the LAI measurements, a "destructive" procedure was used, consisting in a leaf removal from plants with a subsequent leaves measurement by means of a leaf area meter.

Finally, the leaf temperatures, for every species and in both the upper and lower layers of the canopy, were taken using an infrared thermometer, in order to obtain a more representative value.

Proper ranges of the cited parameters have been found for each species. A more detailed description of the measurement campaign is presented in (Ferrante, 2016).

Figure 4.1. Plant species investigated in this study.

As for the leaf temperature, its dependence on climatic parameters has been analysed as well and a correlation with some meteorological variables was estimated. In particular, the obtained distribution of experimental points for both the solar radiation and the air temperatures highlighted a linear equation as the best fitting curve (Figure 4.2). Graphs show that the correlation between the foliage temperature and the solar radiation is stronger compared to the one between the foliage temperature and the air temperature, as confirmed by the obtained autocorrelation coefficients values. This could have been expected, considering that leaves are more affected by the presence and/or absence of direct solar than by the air temperature, the response to the modifications of such parameter is in fact slower.

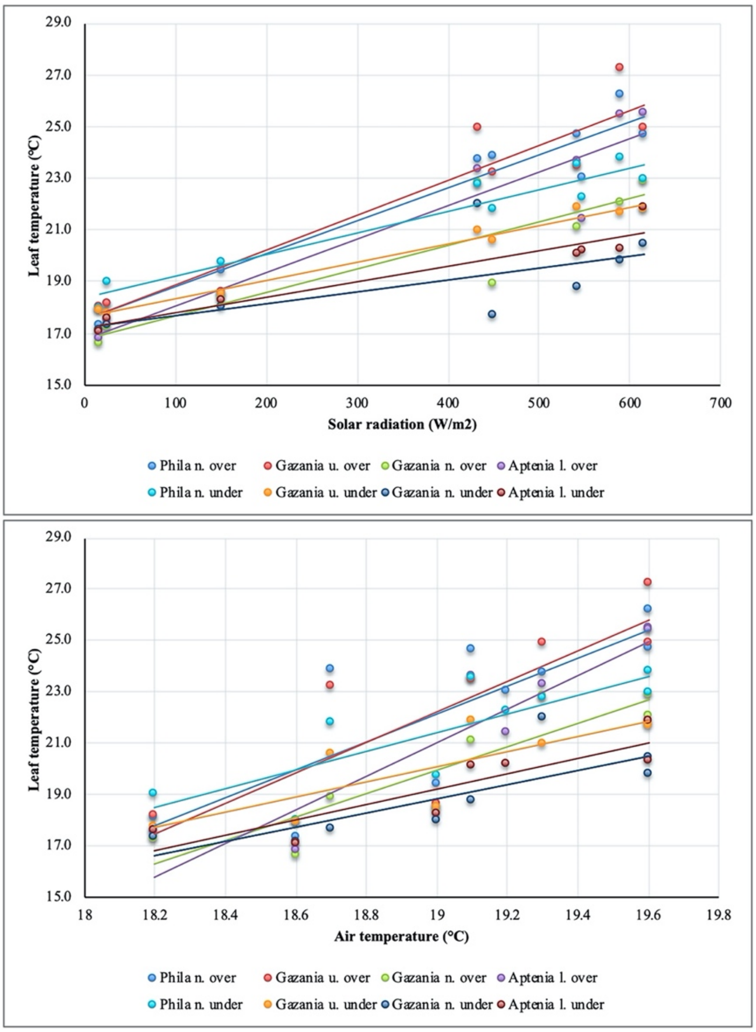

Figure 4.2. Leaf temperature opposite solar radiation (up) and air temperature (down), adapted from (Ferrante, 2016).

Clearly, in the aim of realizing a continuous and homogeneous green coverage to reduce the impact of solar radiation on the building roof, the thickness of the water storage layer also plays a role in the optimization of the components, other than the type of plant species, which is the most important factor. In this respect, we also conducted a monitoring campaign where the ceiling temperatures were measured in some rooms sited below an experimental green roof consisting of different plots, characterized both by distinct water storage thickness and plant species (Cirrincione, 2020). As expected, results pointed out a general propension in achieving lower temperatures when the green coverage is taller and when the water storage layer is thicker; a ceiling temperature difference comprised between 1 and 3 °C was registered with respect to the plots presenting lower green coverages and thinner water storage layers.

4.3 The Environmental Impact of a Green Roof

Provided that, as mentioned in the Introduction section, vegetated roofs have become increasingly popular in urban contexts, in our opinion it seems quite relevant understanding the actual environmental impact of such components, in order to understand whether their large-scale implementation might be a cause for concern.

4.3.1 The Life Cycle of the Substrate: a Lack of LCA Studies on Green Roofs

Although in recent years the growing interest in green roofs has led to a growth of the number studies regarding their overall performance, especially from a thermal point of view, and their effectiveness in different climatic contexts, (Bevilacqua, 2016; Bevilacqua, 2020), specific environmental analyses regarding the substrate, currently available in literature, seem to be somehow lacking (Zhao, 2014; Sailor, 2011; Koura, 2017). Indeed, based on a literature review performed by the authors on green roof studies addressing environmental analyses of these components, it has emerged that the role of both the substrate and the disposal phase on the overall environmental impact of the green roof (Peri, 2012) is currently underestimated.

Two interesting studies about green roof performances and their comparison with standard roofs (Saiz, 2006; Kosareo, 2007) analyse such building components by means of the well-known life cycle assessment (LCA) methodology. This is an internationally standardized procedure (ISO 14040 and ISO 14044) and essentially allows estimating the potential environmental impacts of given product /service though its entire life cycle on a given set of impact categories such as, for instance, global warming, eutrophication, acidification, representing these latter well-known environmental issues. Nevertheless, both the analyses result not being fully exhaustive comprehensive: concerning the one performed in (Saiz, 2006), this observation is mostly linked to the disposal phase being completely overlooked, while regarding the study reported in (Kosareo, 2007), it principally relates to the LCA lacking of a green roof significant element, i.e. the growing medium.

4.3.2 An LCA Contribution Towards More Complete and Proper Analyses of the Whole Environmental Impact Exerted by a Green Roof During its Whole Life Cycle

In order to contributing in covering this gap and thus allowing a full and accurate utilisation of the LCA methodology to achieve a more comprehensive description of the environmental performances of this building component, without the vegetation layer tough, a classical LCA methodology has been applied to a specific extensive green roof, built on the top of a Research Institute building sited in a small Sicilian town near Palermo (Italy). The entire life cycle of the substrate has also been included in the analysis, besides taking into account also the end of life of the green roof.

Green roof data related to the vegetation have not been considered in the analysis as it was not possible to obtain primary data (such as water and fertilizers) from the owners and/or handlers. Nevertheless, this is a typical limitation when one tries to carry out the LCA of a green roof (Saiz, 2006, Kosareo, 2007).

A comprehensive description of the inventory phase and impact assessment phase is reported in (Peri, 2012).

The outcomes of the study (briefly summarized in Figure 4.3) have underlined the importance of including the substrate in such kind of analyses. More specifically, from our analysis it has emerged that the presence of the substrate should not be overlooked because the substrate, compared to the others elements, plays a significant role in the environmental impact of the end of life phase of green roofs. In fact, we have discovered that the substrate disposal in landfill (treatment hypothesized in the analysis) causes a dramatic Aquatic Toxicity potential.

It is also worth noting that the substrate requires the use of substances such as fertilizers that in the common environmental impact of buildings would not be normally considered. In other words, when performing an LCA of a building, whose roof is different from a green roof, the use of fertilizers is generally not contemplated because no cultivation soil is involved. As that, the environmental impact of a building without a green roof is not commonly influenced by these substances. Considering the impact of fertilizers is important, because fertilizers cause on one hand NOx and N2O emissions during the use phase of the green roof and, on the other hand, their production process causes a high Eutrophication and Terrestrial Toxicity potential, as resulted in our study (Peri, 2012).

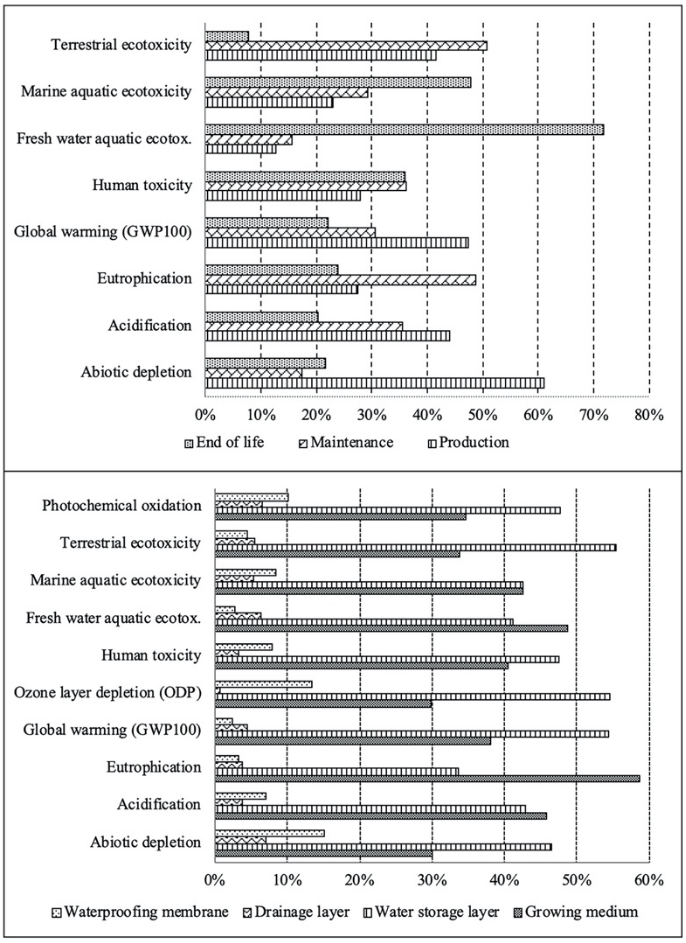

Figure 4.3. Summarized characterization results of the LCA showing the weight of the substrate on the environmental impact of the green roof, adapted from (Peri, 2012).

4.4 The Economic Impact of a Green Roof

As mentioned in the Introduction section, vegetated roofs have become increasingly common in urban contexts, especially for the many benefits they are capable to provide. In light of that, the knowledge of the actual cost of such technology from a life cycle perspective appears of no negligible importance too. In fact, obviously the feasibility of the adoption of the green roof as a building component depends on its life cycle cost. If this is too high, then this solution will not be economically viable and probably to be discarded despite all the technical advantages it provides.

On the other hand, from the standpoint of people occupying a given building (tenant and/or owner) and thus paying the current costs of the electric energy, indeed reduced by the presence of the green roof, it might be useful to have at disposal simple but reliable criteria for assessing the economic feasibility of green roofs compared to other roofing options during the duty phase of the building.

4.4.1 The Life Cycle of the Substrate: a Lack of LCA Studies on Green Roofs

Although over the last years the economic evaluation of green roofs has gained more attention (Shafique, 2018; Shafique, 2020; Ulubeyli, 2017), along with the environmental one, literature put in evidence how some components of the green roof life cycle cost analysis are often not taken into consideration. Specifically, the role of the disposal phase seems to be underestimated and/or lacking (Peri, 2012).

4.4.1.1 An LCC Contribution Towards More Complete Analyses of All Life Cycle Cost of a Green Roof

In order to contribute to the overcoming of this gap, we applied the Life Cycle Costing (LCC) methodology suggested by D. G. Woodward (Woodward, 1997) (that seems being one of the most utilized and generalizable) to a real extensive green roof, by also extending it to the disposal phase, which was missing in previous LCC and Benefit-Cost Analyses (BCA) studies. This case study (Peri, 2012) also allowed to perform a complete and proper application of the LCC methodology to achieve an economic evaluation of this component, at least for the abiotic components (vegetation in not, indeed, included in the present study). Results of the study have been elaborated and the following Table 4.3 has been carried out.

As it can be observed, from the analysis it emerged that the cost for the disposal of an extensive green roof has only a slight incidence on its total life cycle cost. In addition, the analysis showed that the cost of the disposal of the substrate seems to be the main responsible for the disposal cost of the whole roof (85%). The same conclusion can be drawn with respect to the initial capital cost, where the substrate resulted responsible for 44% of the total cost (Peri, 2012).

Table 4.3. Cost components of the analysed green roof life cycle.

Cost components	Total green roof [€]	Functional unit 1 m^2 [€]	[%] incidence
Initial investment cost	6,154	75 (for purchase of materials and installation)	36%
Maintenance cost hypothesizing a life span of 40 years	10,100	123 (for adding substrate and inspection to remove infesting and fertilizing)	60%
End of life cost for the hypothesized scenario	784	9 (landfill and incineration)	4%
The total life cycle cost	17,000	207	100%

4.4.2 A Contribution Towards a Simplified Economic Appraisal of the Feasibility of Green Roofs

Obviously, when analysing an important building component such as a green roof, economic aspects also need to be taken into consideration.

Results of a simple procedure to estimate the green roofs' economical effectiveness has also been briefly summarized here (Figure 4.4), based on a previous study conducted by the authors (Di Lorenzo, 2019), in which the evaluation of the periods of time in which a certain building requires an active cooling support in order to maintain the required indoor comfort conditions (estimated service time) has been transformed into the cost of the corresponding needed electric energy. Specifically, Figure 4.4 comparatively shows the specific costs (kWh/m^3) for the ex-ante and the enhanced albedo scenarios of two Sicilian cities, Palermo and Messina.

The choice of an economic criterion concerning the running cost of the air conditioning system relies on the consideration that people usually decide to rent a building where to live based on the running cost of the HVAC systems.

As it can be observed, at least in the performed analysis in both cities a higher reduction of the climatization costs has resulted when installing cool paints or cool membranes on the existing roofs rather than in case of adoption of green roofs. Despite some simplifying assumptions, (some of them typically made in building simulation) clearly affecting the results, this method can represent a preliminary and useful tool to support decision makers when assessing the economic feasibility of these two technological alternatives.

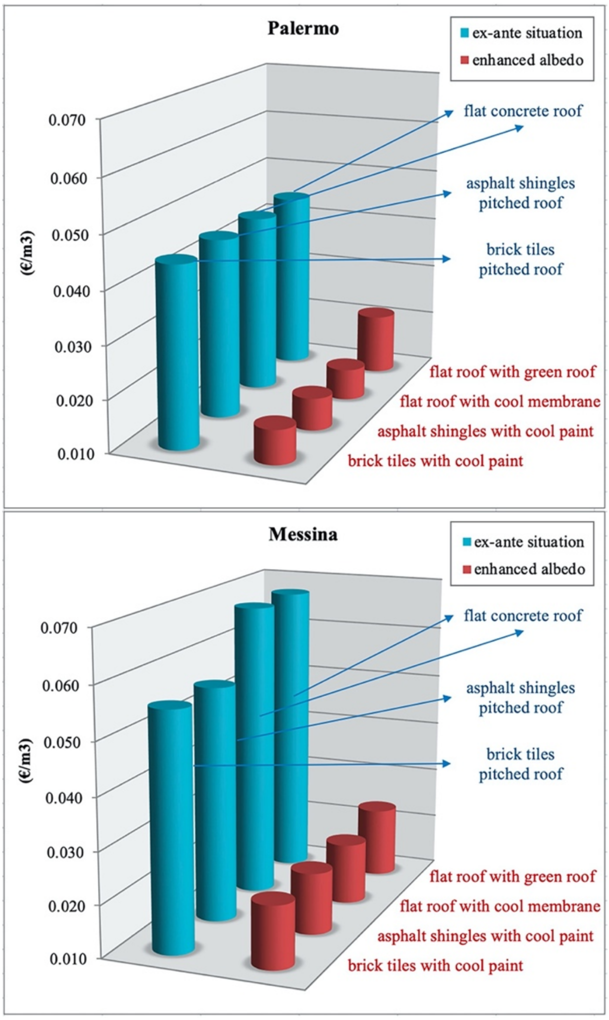

Figure 4.4. Electric energy costs reduction of buildings with green roofs, adapted from (Di Lorenzo, 2019).

4.5 Conclusion

This chapter deals with an increasingly important passive component of the building envelope, which is green roof. Some of the current gaps affecting the energy modelling, as well as the environmental and economic assessment of these building components have been presented. Contributions to their solution, which have arisen from both experimental and modelling research carried out by the authors, have been addressed in this chapter. Specifically, part of it provides a contribution in overcoming the current gaps related to the Life Cycle Costing (LCC) analyses phases, by taking into account the green roof disposal costs. In detail, it has arisen that the cost for the disposal of an extensive green roof has only a slight incidence on its total life cycle cost (4%).

The lack of knowledge regarding the substrate in the application of the classical LCA methodology, as it has been demonstrated, also represents a critical aspect, which negatively affects green roofs' energy performance assessment. This issue has also been dealt with, by reporting results of an LCA conducted on a green roof (whose greening type is extensive) where the analysis of a specific substrate was properly included, by also considering the role of fertilizers used for the green roof maintenance. Specifically, it has been found that the substrate is the greatest contributor to some impact categories such as Fresh Water Aquatic eco-toxicity (49%), Eutrophication (59%), and Acidification (46%).

In addition, the absence of a proper database containing information (growth stage, leaf area index and coverage ratio) relative to the parameters characterizing different green roof plant species, which technicians could use when a lack of field data occurs, has been pointed out. Besides, an estimation of the errors, likely occurring when using not specific vegetation data for an energy estimation of a building equipped with a green roof, is presented; it has resulted that significant errors (up to 45% in the case of heating and up to 24% in the case of cooling) in the estimation of thermal loads might occur when using generic data for the vegetation parameters of an extensive green roof.

Finally, in order to provide building's users (i.e. people occupying a given building, which are thus responsible for the energy bill) with an easy and yet effective tool for assessing the economic viability of green roofs, some observations regarding the economic appraisal of green roofs have been included as well.

In conclusion, based on considerations presented in this chapter, further analyses are highly recommended. In fact, there are still several research areas and technical difficulties that need to be addressed, as for instance the evaluation of the initial high construction and maintenance costs in sight of a proper economical evaluation (Tassicker, 2016; Mahdiyar, 2016), or the consideration of possible leakage occurrences (Baryła, 2018).

Furthermore, another aspect that emerged from the research activity on green roofs carried out so far by the authors, regards the importance of the availability of adequate simulation tools (Mazzeo, 2015; La Gennusa, 2019), in order to facilitate both the design and assessment processes. Green roofs represent an increasingly important building passive component in urban contexts due to the many benefits that can be attributed to them. Green roofs allow indeed to reduce the air pollution

Chapter 4 References

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Chapter 5 - Green Roofs as Effective Tools for Improving the Indoor Comfort Levels of Buildings—An Application to a Case Study in Sicily

This chapter consists in the following journal paper:
Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., Aprile, S., Green roofs as effective tools for improving the indoor comfort levels of buildings-an application to a case study in Sicily (2020), Applied Sciences (Switzerland), 10 (3), art. no. 893.
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Abstract: In the line of pursuing better energy efficiency in human activities that would result in a more sustainable utilization of resources, the building sector plays a relevant role, being responsible for almost 40% of both energy consumption and the release of pollutant substances in the atmosphere. For this purpose, techniques aimed at improving the energy performances of buildings' envelopes are of paramount importance. Among them, green roofs are becoming increasingly popular due to their capability of reducing the (electric) energy needs for (summer) climatization of buildings, hence also positively affecting the indoor comfort levels for the occupants. Clearly, reliable tools for the modelling of these envelope components are needed, requiring the availability of suitable field data. Starting with the results of a case study designed to estimate how the adoption of green roofs on a Sicilian building could positively affect its energy performance, this paper shows the impact of this technology on indoor comfort and energy consumption, as well as on the reduction of direct and indirect CO_2 emissions related to the climatization of the building. Specifically, the ceiling surface temperatures of some rooms located underneath six different types of green roofs were monitored. Subsequently, the obtained data were used as input for one of the most widely used simulation models, i.e., EnergyPlus, to evaluate the indoor comfort levels and the achievable energy demand savings of the building involved. From these field analyses, green roofs were shown to contribute to the mitigation of the indoor air temperatures, thus producing an improvement of the comfort conditions, especially in summer conditions, despite some worsening during transition periods seeming to arise.

Keywords: innovative envelope; building components; green roofs; indoor comfort; energy consumption; building modelling; simulation models

5.1 Introduction

The reduction of energy consumption and the related decrease of greenhouse gases emissions represent important aspects to which much attention has been paid at global, European and countries levels, especially with regard to the building sector.

Worldwide, energy consumption in the building sector is responsible for 36% of total energy use (corresponding to a 39% of energy-related CO_2 emissions) [1,2], while at the European level, the energy consumption in the same sector accounts for a share of the total energy comprised between 25% and 40% (corresponding to about 35% of CO_2 emissions throughout Europe) [3–5].

From this perspective, various strategies have been implemented. At the global level, the UN 2030 Agenda for Sustainable Development, along with the 17 Sustainable Development Goals (SDGs) [6], need to be mentioned.

At the European scale, the EU has been very committed to this issue by setting the well known ambitious targets for 2020 ("climate and energy package") [7], and even more so for 2030 ("climate and energy framework") [8, 9] and 2050 ("long-term strategy") [10, 11]. Other relevant goals have been set out in the seventh Environment Action Program (EAP) [12] aimed at decarbonizing and making more sustainable European cities. Among European standards and regulations issued on this matter, the EPBD Directive and its recast must be cited [13–15].

Italy's National Energy Strategy 2017 [16] lays down the actions to be achieved by 2030, in accordance with the long-term scenario drawn up in the EU Energy Roadmap 2050, which translate to a reduction of emissions by at least 80% from their 1990 levels.

However, despite these standards and regulations being in force, in recent years, the energy consumption in the building sector has increased, particularly in Italy [17]. That is why more effort in promoting actions and finding new strategies to improve energy savings and efficiency are necessary [18].

Generally speaking, apart from all the design strategies typical of the principles of bioclimatic architecture (such as, for instance, space organisation, wall-window-ratio, orientation, thermal mass, operation management [19, 20]), more relevant energy savings achievable in buildings can be attributed to two main categories of components: technical plants (HVAC system) and the building envelope, which have a synergistic relationship. In fact, a reduction in energy consumption related to the HVAC consists in the use of active systems which entail further energy consumption. As regards the building envelope, passive systems (not energy depending) can be used, which allow to actually obtain a reduction of the energy consumption (and at the same time, to also save on the use and the size of the HVAC system). Clearly, the occupants' behaviours and attitudes might also significantly influence energy saving, as demonstrated, for instance, in [21–24]. Starting from the above considerations, in this work, it was decided to pay attention to the use of a passive system to be applied to the building envelope, that is, green roofs equipped with different vegetation types.

Among the passive systems, green roofs are becoming more and more popular due to their capability of reducing the energy needs for the climatization of buildings [25–27], especially for cooling purposes [28–30].

At the same time, vegetated roofs also have a positive impact on the outdoor urban environment in terms of regenerative sustainability, allowing to induce various environmental benefits [26, 31], such as reducing air pollution [32, 33], mitigating noise [34, 35], improving the management of runoff water [32, 36, 37], easing the urban heat island (UHI) effects [38–40], and increasing the urban biodiversity [41, 42]. Moreover, the European Union is evaluating the possibility of including criteria specifically referring to green coverings within the EU Ecolabel scheme for buildings [43].

In addition to experimental studies [44–46], the effect on the built environment of vegetated roofs in diverse climates has also been investigated from analytical [47–49] and modelling points of view [50–52] over the years. In particular, the relevant parameters for energy modelling of green roofs have been explored in the literature, particularly referring to the role played by leaves and solar radiation in the thermal exchanges between vegetated layers and the surrounding environment [53].

The reported literature indicates that green roofs represent very promising building components, also in the Mediterranean context, as demonstrates the incremental number of studies and analyses carried out in recent years concerning both the experimental [44, 54] and the simulating approach [47, 55].

Other studies have underlined that additional issues would probably need more attention regarding plants growing on the roof, especially their influence on the thermal performance of green roofs [56, 57], and the influence of the evapotranspiration component on the green roof heat and mass transmission [50, 58].

Taking into account the studies reported above, it is evident how green roofs can have a strong impact in attenuating the average radiant temperature on building roofs [44, 59, 60]. This capability of acting as thermal insulation positively influences the indoor comfort conditions for the occupants of the rooms sited under the roof [27, 45, 61, 62]: this aspect has always been critical in the design phase of a building envelope.

Kuan-Teng Lei et al. [63], by means of a field experiment performed in a school building in Taipei, have developed a finite element analysis model for the improvement of indoor thermal comfort in the presence of extensive green roofs. The researchers found a decrease of the indoor temperature up to 4 °C, compared to bare roofs. Costa Junior et al. [64], through an experimental analysis conducted in the city of Recife, Pernambuco (Brazil), compared the performance of four roofs made up of chanana green roof (Turnera subulata), daisy green roof (Sphagneticola trilobata), parsley green roof (Ipomoea asarifolia), and fiber cement tile. Through the comparison, the index of discomfort (ID), effective temperature (ET) and the human comfort index (HCI) were calculated. The three vegetated options mitigated both the internal air temperature with a reduction of 0.71°C, 0.19°C and 0.35°C, respectively and the internal surface temperature with a reduction of 1.5°C, 0.8°C and 0.8°C, respectively, compared to the fiber cement tile-made roof. Di Giuseppe and Orazio [65] experimentally analysed the effect of cool and green roofs compared to traditional ones in a Nearly Zero Energy Building, on the internal comfort and the air temperatures of the surrounding environment. The outcomes, on one hand, confirmed the effectiveness of green and cool roofs for the mitigation of the Urban Heat Island effect, and on the other hand, indicated the little effectiveness of high-albedo materials on roofing systems with a very low U-value for internal comfort.

Furthermore, the impact of green walls on thermal comfort have been compared to that of green roofs. For instance, Malys et al. [66], using the SOLENE-microclimat tool, compared the effect caused by different "greening strategies" on buildings' energy consumption and indoor comfort in the summer season. The outcomes of the investigation indicate that, while green roofs seemingly mainly affect the upper floor, green walls directly affect the indoor comfort throughout the entire building.

To help to provide a contribution to this important and often overlooked matter, the aim of this paper was to assess the influence that green roofs have on the indoor thermal comfort levels, particularly considering the indoor radiative heat exchanges. For this purpose, a case study was conducted to estimate how the adoption of the proposed interventions could impact the indoor thermal comfort and the energy consumption of a building and contribute to the reduction of the direct and indirect CO_2 emissions. In particular, the ceiling temperatures of some rooms located underneath six different types of green roofs were monitored. The choice of detecting this parameter resides on the circumstance that the ceiling internal surface's temperature is a relevant component of the mean radiant temperature of the room that, in turn, greatly affects the value of the indoor parameter PMV [67]. Subsequently, the obtained data were used as input data for one of the most widely used simulation models (EnergyPlus [68]) to evaluate the indoor comfort levels and the achievable energy demand savings of the involved building.

Three scenarios were adopted. Scenarios #1 and #2 refer to a building equipped with a green roof; Scenarios #3 refers to the pre-existing roof. The simulation of Scenario #2 is made by means of the Energy Plus code, through its resident routine; on the other hand, Scenario #1 is modelled by imposing, for the indoor temperatures of the ceiling, the experimental data detected on the site. The aim of this approach was to compare the PMVs obtained from Energy Plus with those calculated on the basis of the monitored experimental data, i.e., the indoor ceiling surface temperatures.

5.2 Marerials and methods

The presented study is part of a joint research project between the University of Palermo and the "Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria - CREA", operating in Sicily. To accomplish the task mentioned in the Introduction, a mixed approach, partly modelling and partly experimental, was used in the work.

At the same time, the impact that green roofs have on the energy consumption of a building was evaluated. In addition, the estimation of the achievable savings in direct and indirect CO_2 emissions due to the use of such building component is reported as well.

5.2.1. Description of the Experimental Site

The installation of the experimental green roof was settled by the CREA Research Center and the University of Palermo with the support of a building materials enterprise, on the roof of a one-storey detached house (Figure 5.1) owned by CREA and sited in Bagheria, a Sicilian town near Palermo (Southern Italy).

To conduct the present case study, it was decided to install the green coverage on the pre-existing roof of the building, made of hollow bricks, with a surface of approximately 80 m^2.

Figure 5.1. Site of the installation of the experimental field (source: Google-Earth).

As regards the weather conditions of the site, they were typical of the South of Italy, characterized by a temperate climate with warm summers and mild winters. Figures 5.2, 5.3 and 5.4 show the trend of outdoor air temperature (T), relative humidity (RH) and solar radiation (IR), respectively, during the monitoring period of one year.

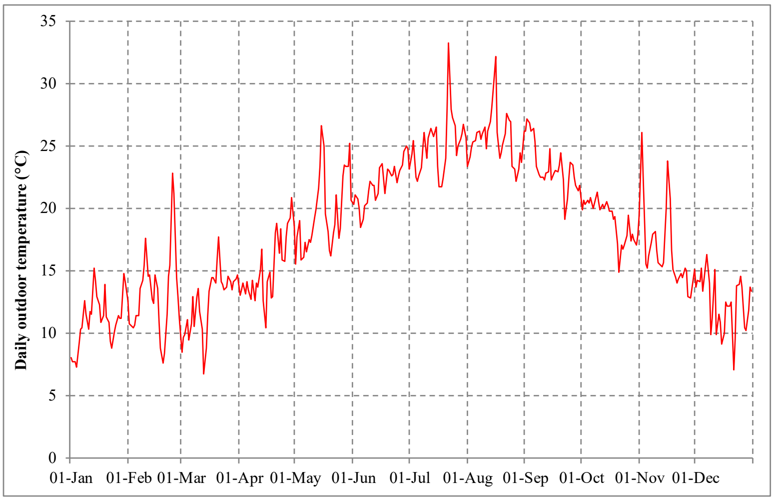

Figure 5.2. Trend of the outdoor air temperature during the monitoring period.

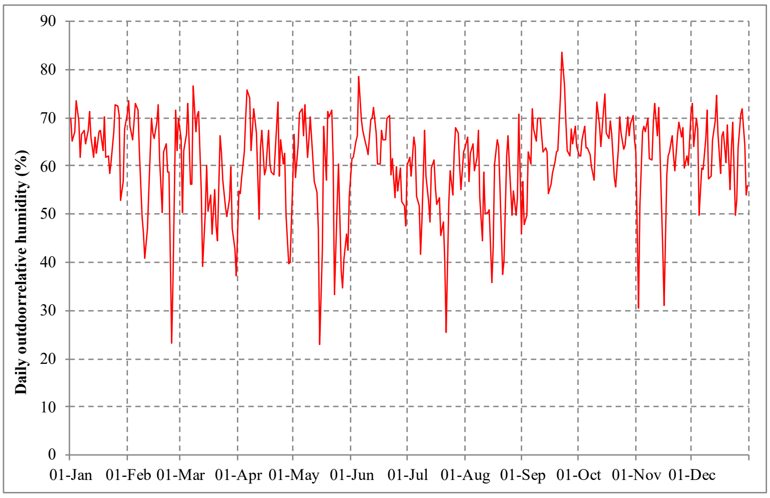

Figure 5.3. Trend of the outdoor air relative humidity during the monitoring period.

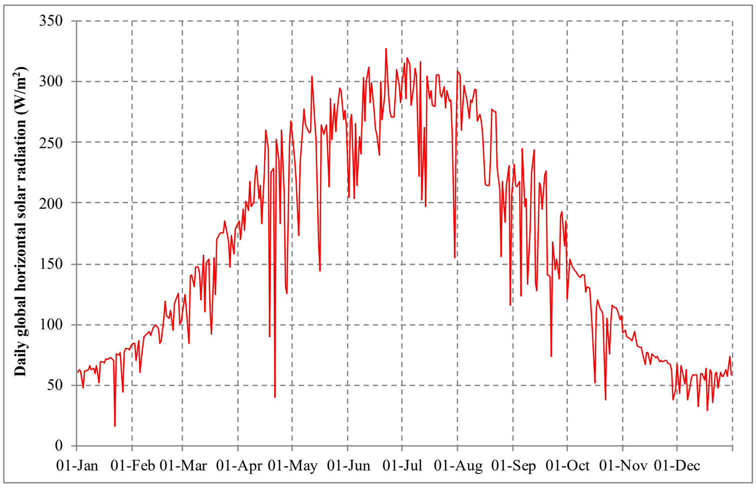

Figure 5.4. Trend of the solar radiation during the monitoring period.

5.2.2. Description of the Analysed Green Roof Installed in the Experimental Site

Going from the indoor to the outdoor sides of the building, as shown in Figure 5.5, the green roof compound is composed of the following layers: a root barrier (with a waterproofing membrane), a drainage layer (made of a polyethylene geo-net, hot-coupled with a non-woven geotextile with filtering functions), a water storage layer (constituted by cushions filled with expanded perlite), a filter fabric (composed by a geotextile felt, 100%polypropylene calendered), a growing medium (which is a mixture of peat, lapillus, pumice, zeolite and slow releasing fertilizers and is infesting weeds free) and the vegetation layer.

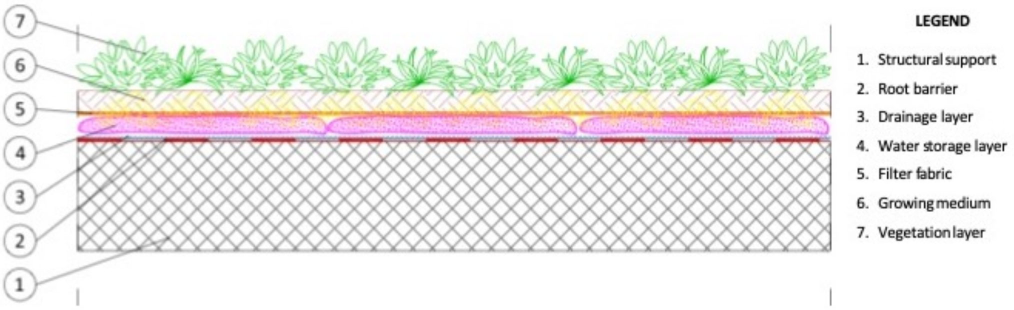

Figure 5.5. Sketch of the green-roof layers.

In order to also analyse the effects provided by different plant species and different thicknesses of the water storage layer on the green roof thermal behaviour, the roof was divided into six sectors, where three different Mediterranean autochthonous species (*Halimione Portulacoides*, *Rosmarinus Officinalis Prostratus* and *Crithmum Maritimum*) and two different thicknesses of the water storage layer (10 cm for plots 1, 2, 3 – P1, P2, P3 – and 15 cm for plots 4, 5, 6 – P4, P5, P6 –) were used according to the scheme reported in Figure 5.6.

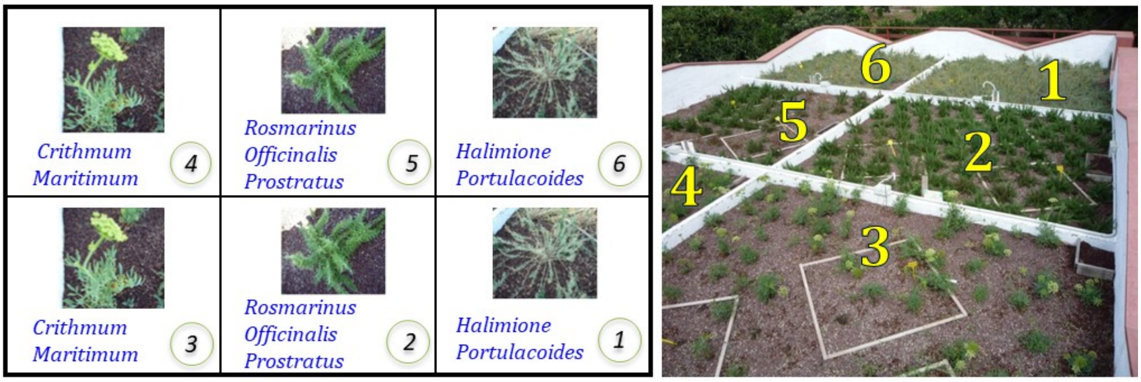

Figure 5.6. Scheme of the plant species planted in the different sectors.

A brief structural description of each layer is reported in Table 5.1.

Table 5.1. Description of the layers constituting the green roof plot.

Layer	Element type	Thickness [cm]	Plant species
1	Structural support	20	*Hollow brick*
2	Waterproofing membrane and root barrier	-	*Bituminous paint*
3	Drainage layer	0.5	*Polyethylene geo-net, hot-coupled with a no woven geotextile*
4	Water storage layer	10 (P1, P2, P3) 15 (P4, P5, P6)	*Pillows filled with expanded perlite*
5	Filter fabric	-	*Geotextile felt, 100%polypropylene calendered*
6	Growing medium	15	*Pumice, lapillus and peat*
7	Vegetation layer	-	*Halimione Portulacoides* (P1 and P6) *Rosmarinus Officinalis Prostratus* (P2 and P5) *Crithmum Maritimum* (P3 and P4)

Table 5.2 reports, instead, the main physical parameters characterizing each of the green roofs' six plots. The data listed in Table 5.2 are the same as those used in [69].

Table 5.2. Description of the layers constituting the green roof plot.

Parameters	Plots					
	P1	P2	P3	P4	P5	P6
Water storage layer thickness (cm)	15	15	15	10	10	10
Height of Plants (m)	0.35	0.28	0.12	0.12	0.22	0.30
Leaf Area Index (-)	4.0	2.8	1.2	0.9	2.3	3.8
Leaf Reflectivity (-)	0.19	0.18	0.17	0.20	0.21	0.21
Substrate total thickness (m)	0.30	0.30	0.30	0.25	0.25	0.25
Thermal conductivity of dry soil (W/m·K)	0.0738	0.0738	0.0738	0.0816	0.0816	0.0816
Density of dry soil (kg/m^3)	530	530	530	446	446	446
Specific heat of dry soil (J/kg·K)	1050	1050	1050	1060	1060	1060

In addition to thermal conductivity, density and specific heat, which characterize the thermo-physical behaviour of the soil, some other properties typical of the specific plants, which have an important impact on the heat exchanges through the green-roof, were also considered.

Particularly, the "leaf reflectance" (dimensionless), that is, the ratio of the incoming light which is reflected by a leaf, and the "leaf area index"—LAI (m^2/m^2)—defined as the one-sided green leaf area per unit of ground surface area. The latter, in particular, which has a great influence on the shading and transpiration effects, has a positive effect, especially during summer seasons; in fact, the higher the LAI, the higher the cooling reduction [50, 69, 70].

As for the vegetation characteristics, Figure 5.7 shows how the *Halimione Portulacoides* (both P1 and P6) and the *Rosmarinus Officinalis Prostratus* (only P5) reached full coverage (100%) in less than 12 months while the *Rosmarinus Officinalis Prostratus* in P2 achieved a maxim coverage of about 85% in the same period and the *Crithmum Maritimum* (both P3 and P4) did not accomplish more than 40%–60%, showing the difficulty of establishing it in the considered environment [52].

Figure 5.7. The six-plots green coverages system.

5.2.3. Data Monitoring System Adopted

The field experimental part of the proposed approach essentially consisted in a monitoring campaign of the ceiling temperature values of the building.

Since the monitoring of the temperatures profiles of the ceiling was aimed at checking the effects of the presence of the green roof on the indoor conditions, particularly in terms of thermal comfort levels, measures were performed in the center of the rooms' ceiling, far from thermal bridges and lights fixtures, as shown in Figure 5.8.

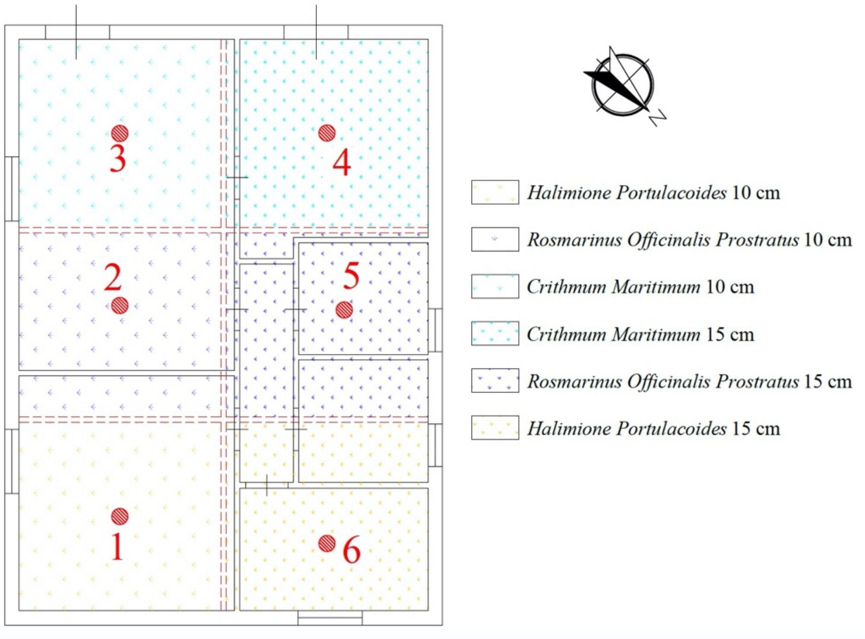

Figure 5.8. Layout of the building, green roof plots' arrangement and positions of probes for the temperature measurement.

Concerning the measuring method, temperatures were recorded with a sample rate of 10 minutes, during both the winter and the summer seasons, by means of insulated T type thermocouple probes.

The monitoring campaign lasted one year and started six months after the installation of the green roofs in order to have the green coverage well stabilized and to allow the testing of the acquisition system.

5.2.4. Simulations Performed in the Study

The modelling part of the proposed approach consisted in utilizing the very popular EnergyPlus simulation code to run the building's thermal calculations. For this purpose, different scenarios were implemented, specifically:

- Scenario #1, in which the monitored ceiling temperatures were utilized in the simulation as boundary fixed conditions for the ceiling of the investigated rooms. In this scenario, a detailed schedule for the HVAC was implemented, based on assumptions made of its "real" use according to the typical time of occupation of the building, considering a power capacity of 10000 Watt. This value was obtained from simulations previously conducted using the climatic design-day typical of the examined area, characterized by a temperature of 5.2°C (± 0) for winter conditions and 31°C (± 6) for summer conditions.
- Scenario #2, in which the simulation was carried out utilizing the green roof configuration provided by EnergyPlus (EP+GR), trying to simulate the

previously described six plots as faithfully as possible by using the parameters reported in Table 5.1 and Table 5.2. In fact, the EnergyPlus green roof simulation tool sets numerical limits for some parameters, which could not therefore have been set according to their real values.

- Scenario #3, in which the simulation was conducted by implementing a standard case (STD), that is, considering the original roof of the building without the presence of green coverage.

Regarding the HVAC schedule of Scenario #2 and Scenario #3, it was decided to use a simple on/off schedule, with the HVAC working between 7:00 and 17:00, considering the same power capacity as that used in Scenario #1.

The authors would like to underline here that Scenarios #1 and #2 are characterized by the presence of green roofs, while Scenario #3 refers to a standard roof. The difference consists in the fact that, while the simulation of Scenario #2 totally complies with the Energy Plus code (by utilizing its typical green roof simulation routine), Scenario #1 is modelled by forcing the Energy Plus code, that is, imposing the monitored indoor ceiling temperatures as boundary conditions. In this way, the model was driven with real data based on the presence of the experimental green roof, avoiding the actual simulation of the green roof element itself. Hence, this allowed us to compare the PMVs obtained from the Energy Plus green roof simulation tool (with its relative assumptions limits) with those calculated on the basis of the real monitored experimental data.

In order to assess the direct and indirect reduction of CO2 emissions, in this work, a value of 85 kgCO2/ha per year [71] was considered for the direct reduction of CO2 emission, based on the extension of green covering, while a value of 0.531 tCO2/MWh (the average emissions for the current electric Italian energy mix [34]) was used to estimate the indirect reduction of CO2 emission based on energy saving for climatization purposes and having set a COP value equal to 3 for the cooling season and 3.5 for the heating season.

5.3 Results amd Discussions

In this section, the results relative to the monitoring campaign and to the energy performance simulations are reported.

5.3.1. Monitored Data

Table 5.3 shows the average temperatures measured on the ceiling of each room sited below the green roof’s six plots, for summer (July) and winter (February) conditions, in periods during which the air-conditioning system was working.

Table 5.3. Monitoring results of the green roofs six plots.

Plots	Plant species	Water storage layer thickness (cm)	Maximum green coverage (%)	T_{avg} (°C) of the ceiling	
				February	July
P1	*Halimione Portulacoides*	10	100%	18.1 ± 2.1	26.6 ± 0.2
P2	*Rosmarinus Officinalis Prostratus*	10	85%	16.0 ± 1.8	27.5 ± 0.9
P3	*Crithmum Maritimum*	10	58%	15.8 ± 1.4	26.9 ± 1.1
P4	*Crithmum Maritimum*	15	38%	17.9 ± 1.2	30.8 ± 0.8
P5	*Rosmarinus Officinalis Prostratus*	15	100%	17.6 ± 1.2	28.5 ± 0.6
P6	*Halimione Portulacoides*	15	100%	19.0 ± 1.1	28.2 ± 0.3

The monitoring results point out a general tendency to attain lower temperatures when the green coverage is higher, i.e., P1 (*Halimione Portulacoides*). Indeed, this plot shows that ceiling temperatures were generally 1–3 °C lower with respect to the other plots in summer and 1–2 °C higher during winter, hence representing a benefit for both the summer and winter seasons.

Moreover, it must be noted that the LAI has a positive influence on the green-roof thermal behaviour; P1 and P6 have, in fact, higher LAI, unlike P3 and P4. In addition, another factor that could have influenced the obtained results is represented by the light colour of the plants' leaf surface, which enabless a higher amount of solar radiation to be reflected.

The results shown in Table 5.3 also highlight the influence of the different type of plants. In particular, *Halimione Portulacoides* (P1 and P6) reduces temperature peaks more consistently. Therefore, this type of plant seems to be more suitable for lowering the summer temperature values and increasing the winter temperature peaks.

Anyway, as reported in Table 5.3, it should be pointed out that during the summer season, a mean temperature of about 26.6 °C has been recorded by the thermocouples placed on the rooms' ceilings under P1 (*Halimione Portulacoides*), with maximum peaks of 27 °C, that lies within the suggested range for the indoor comfort in summer conditions [72]. The same cannot be stated for the other plots, where, even with a 100% green coverage, ceiling temperatures of about 27–28 °C were registered, with maximum peaks going beyond 30 °C.

The above-discussed outcomes demonstrate the importance of selecting a proper plant species during the green roof design phase.

Apart from these considerations, strictly related to the physical characteristics of the green roof, it is also necessary to take into consideration some aspects related to the building features that may have influenced the monitored ceiling temperatures, in particular:

- the room located underneath the plot P1, facing North, is almost always in the shade (and not often sunlit); therefore, it is likely that the indoor environment is characterized by an air temperature lower than that of the other rooms;
- the room sited below the plot P4, on the other hand, is subjected both to greater solar radiation levels on the west-faced external wall and to heat released by several refrigerators aimed at the storage of biomass; it is then possible that the temperature inside such a space is constantly higher than that of the other rooms;
- the sensors located under plots P2 and P3, despite being associated to two different plant species, are located within a single large environment, which could make the distinction of their readings quite difficult;
- the rooms where the sensors relative to plots P3 and P4 are placed in, border on the left with a small greenhouse that, reasonably, is characterized by a higher air temperature than the outdoor.

5.3.2. Outcomes of Energy Simulations

Since the main aim of this work was to assess how the use of green roofs can affect the indoor comfort and the energy consumption of a building, it was decided to report, in the first part of this section, a comparison between the simulation results of Scenario #1 and Scenario #3. In particular, considering that such estimation is affected by the temperature changes during the actual HVAC system operating periods and in light of the detailed schedule utilized to run the simulations, it was chosen to divide the resulting data into two five-days periods representative of winter (Figure 5.9, on the left) and summer (Figure 5.9, on the right) conditions. Specifically, in Figure 5.9, the green lines represent an average of the values obtained for the six plots (Scenario #1), with its relative ranges of variation and the blue lines represent the standard case (Scenario #3); on the other hand, the red lines indicate the HVAC system start-up intervals.

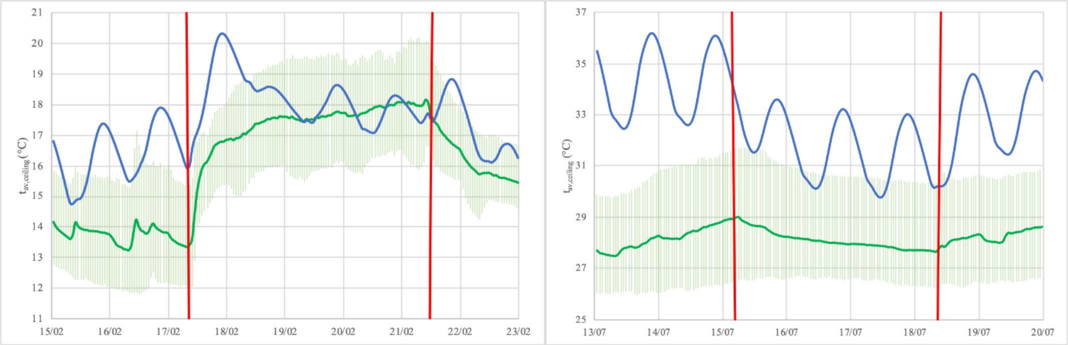

Figure 5.9. Comparison between Scenario #1 (green lines) and Scenario #3 (blue lines) for winter (left) and summer (right) conditions.

Looking at Figure 5.9, it can be noted how after an initial start-up phase of the HVAC system, the presence of a green roof during the winter season does not seem to improve the indoor thermal conditions, while during the summer season, it brings a noticeable improvement of the indoor comfort levels. It must be underlined here that the amplitude of the variation range relative to the green roofs' temperature values is due to the fact that as reported in Section 5.2, the six plots are characterized by different features and therefore, describing parameters; in particular, the type of species and its relative coverage percentage have a strong influence on the monitored temperatures.

The temperature differences noticed also had an impact on the energy consumption. Over the representative five-day periods considered, in fact, a 18% increase for heating needs (220.05 kWh for the standard roof against 259.59 kWh for the green roof) and a 44% saving for cooling needs (189.38 kWh for the standard roof against 106.37 kWh for the green roof) were observed.

As mentioned earlier, after this first comparison, the authors wondered what results would have been obtained by simulating a green roof similar to the real one using the green roof configuration tool provided by EnergyPlus. The second part of this section shows, therefore, a comparison between the results obtained from the Scenario # 1 and Scenario # 2 simulations.

Similarly, to the previously reported Figure 5.9, Figure 5.10 contains the obtained results for the two five-days periods representative of winter (on the left) and summer (on the right) conditions. In particular, the green lines (Scenario #1) and the red lines (HVAC system start-up intervals) are the same as shown in Figure 5.9, while the black lines represent an average of the values obtained for the six plots, with the relative ranges of variation, using the Scenario #2 EnergyPlus settings.

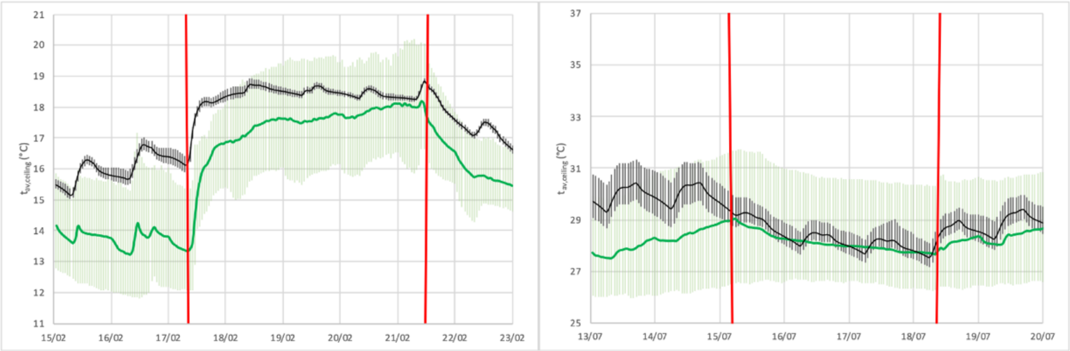

Figure 5.10. Comparison between Scenario #1 (green lines) and Scenario #2 (black lines) for winter (left) and summer (right) conditions.

By analysing Figure 5.10, it can be seen how, in the winter conditions, the green roof simulated according to Scenario #2 shows a very similar behaviour to that in

Scenario #1, particularly during the air-conditioning working periods. In winter conditions, however, Scenario #2 allows to obtain higher temperatures than Scenario #1, corresponding to a further improvement in the indoor comfort levels. Furthermore, in summer conditions, contrarily to Scenario #1, Scenario #2 shows an evident very variable temperature trend between day and night, typical of a context highly influenced from solar radiation, which does not seem to reflect reality.

As for the fact that the changes of the Scenario #2 temperatures range are much narrower than those in Scenario #1, it must be observed that this is most likely due to the fact that, as previously highlighted, the model used by EnergyPlus does not allow to set all the parameters of the green roof freely but imposes some constraints to their numerical values. Due to this reason, in fact, the Scenario #2 results show no differences relating to the two different thicknesses of water storage used for each species, but only some small differences between the different species.

As for the energy consumption of Scenario #2, over the representative five-day periods considered, a 4% saving for heating needs (220.05 kWh for the standard roof against 212.34 kWh for the green roof) and a 41% saving for cooling needs (189.38 kWh for the standard roof against 112.54 kWh for the green roof) were observed.

Finally, in the last part of this section, it was decided to report a rough estimate, on a monthly basis, relative to both aspects of indoor comfort improvement and energy consumption savings. In this regard, it was chosen to compare the results deriving from the simulations of Scenarios #2 and #3. This choice was suggested due to the fact that, given the intended use of the building (i.e., research laboratory) and its real use (i.e., infrequent), especially in terms of the HVAC system, it was assumed that the results of Scenario #1 were not considered actually representative for a long-term estimate.

Once again, in order to make the results visually more easily readable, an average of the results obtained for the green roof six plots was used to display the results of Scenario #2.

To compare Scenario #2 with Scenario #3 in relation to indoor comfort levels, it was decided to report, in Figure 5.11, a graph of the monthly temperatures. The graph indeed allows to show the deviations of the average values of the green roof ceiling temperatures ($\Delta t_{av,ceiling}$) compared to those of the standard roof, where the black bars represent the range of deviation from the average values.

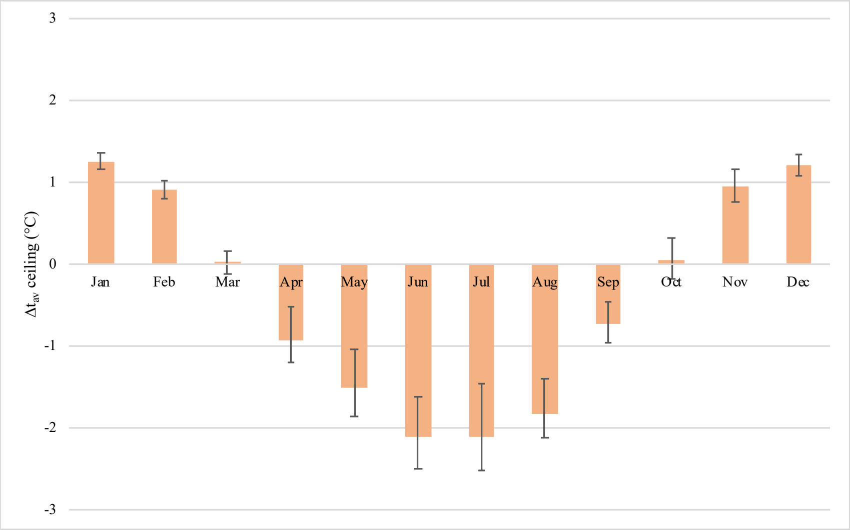

Figure 5.11. Deviations of the average values of the green roof ceiling temperatures compared to those of the standard roof.

Figure 5.11 highlights the positive effects due to the presence of the green roof, which, with respect to the standard roof, allows maintaining higher ceiling temperatures in winter and lower ceiling temperatures during summer.

Other than the temperature, another important indicator when assessing the indoor comfort levels is represented by the PMV (Predicted Mean Vote). For this reason, it was also decided to report, in Figure 5.12, a comparison between the monthly PMV average and peak values of Scenario #2 (GR) and Scenario #3 (ST).

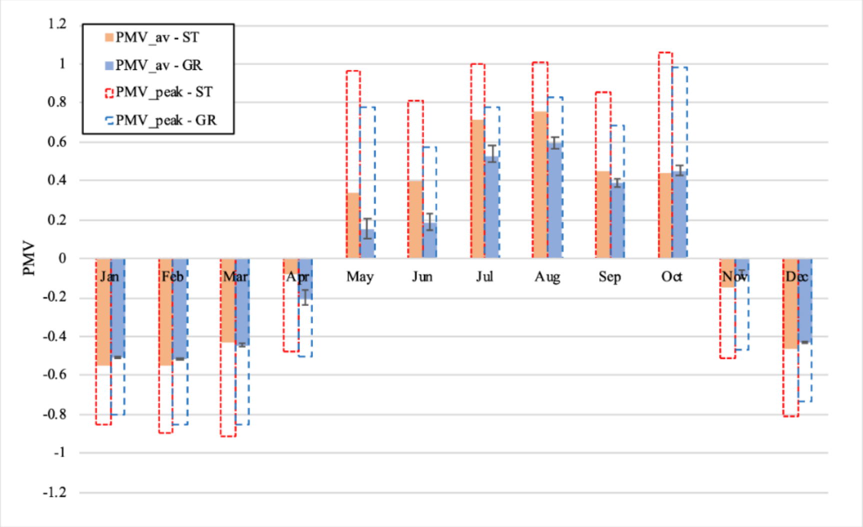

Figure 5.12. Monthly PMV average and peak values for Scenario #2 (GR) and Scenario #3 (ST).

By looking at the differences in the obtained PMV average values (Figure 5.12) with and without the presence of the green roof, especially those relative to July and

August, it arises that the presence of the green roof reduces PMV average values from more than 0.7 to approximately 0.5. Hence, accordingly to the standard currently in force for the design of the indoor environment, i.e., EN 16798-1:2019 [72], the presence of the green roof contributes to shift the indoor thermal environmental conditions from Category III (acceptable, moderate level of expectations) to Category II (normal level of expectation). In other words, the presence of the green roof contributes to bring the building within comfort conditions (PMV = 0.5), starting from a slight warm condition (PMV = 0.7).

Moreover, by analysing Figure 5.12, it can also be seen how, although a general positive effect due to the presence of the green roof is evident, some critical issues emerged in the months of April and October (transition months), for which the standard roof seems to perform better than the green roof. This condition, which needs to be better investigated, is probably due to the additional thermal inertia that the presence of the green roof brings to the structure: this slows down the response of the green roof compound to the changes of climatic conditions occurring in the transition periods of the end of spring (April) and the beginning of winter (October).

For the sake of completeness, it was decided to report, in Figure 5.13, an annual plot where the average daily external temperatures (Outdoor) are compared with those of the ceiling in the presence of the green roof (GR_mean) and with those relative to the standard roof (ST).

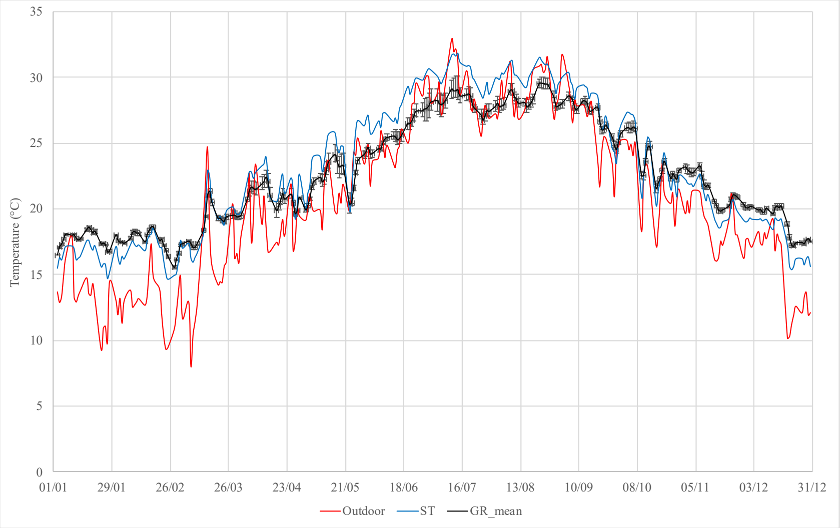

Figure 5.13. Annual average daily temperatures (i.e. $T_{\text{outdoor air}}$, $T_{\text{ceiling with GR}}$ and $T_{\text{ceiling without GR}}$) trends.

Regarding the energy consumptions for heating and cooling needs, these are summarized in Table 5.4 by reporting the absolute values (kWh) obtained for the standard roof scenario and the correlated average percentage deviations (including the respective variation ranges) relative to the achievable savings due to the green roof presence.

Table 5.4. Monitoring results of the green roofs six plots.

		Standard roof (kWh)	**Green roof (% savings)**
Jan	**Heating**	**655.1**	**17.9 ± 1.7%**
	Cooling	0	
Feb	**Heating**	**610.6**	**12.5 ± 1.8%**
	Cooling	0	
Mar	**Heating**	**409.9**	**2.2 ± 3.5%**
	Cooling	0	
Apr	Heating	15.9	-43.6 ± 34.3%
	Cooling	0	
May	Heating	4.4	2.1 ± 24.2%
	Cooling	0	
Jun	Heating	0	
	Cooling	**239.6**	**50.1 ± 9.8%**
Jul	Heating	0	
	Cooling	**534.2**	**28.7 ± 7.4%**
Aug	Heating	0	
	Cooling	**630.0**	**24.7 ± 4.9%**
Sep	Heating	0	
	Cooling	**323.1**	**20.4 ± 4.7%**
Oct	Heating	2.0	62.9 ± 6.7%
	Cooling	45.9	33.0 ± 10.7%
Nov	Heating	69.5	59.3 ± 7.0%
	Cooling	0	
Dec	**Heating**	**429.8**	**26.4 ± 2.5%**
	Cooling	0	

Specifically, for each month, the amount energy consumed for both heating and cooling with and without the presence of the green roof is listed. The use of the bold character is intended to show more easily the actual HVAC working periods, that is December–March for winter conditions and June–September for summer conditions. Therefore, in Table 5.4, data related to months when the HVAC is working have been highlighted using the colour black. The results confirm the advantage of using green roofs as a solution capable of achieving valuable energy savings.

Moreover, the mean indirect reduction of CO_2 emissions due to the green roof installation was 145.6 ± 13.8 tCO_2/year, while for the direct reduction, a value of only 56 gCO_2/year was observed.

Finally, some further considerations need reporting. When an energy restoration of a roof is in context, such as the one considered in this work, it is easier and safer to add a vegetated coverage to an existing roof than making it larger. That is why here, it was chosen to exclude a theoretical comparison between a green roof and a hypothetical alternative high massive one and to limit the analysis to a specific comparison between the behaviour of the pre-existent standard roof equipping the building and the improvements brought by the installation of the green coverage. For this purpose, the thermo-physical characteristics of the roof are those typical of the building habit of the considered geographical area.

In addition, the benefits of the presence of a green roof cannot be simply evaluated in terms of thermal insulation, since it generates other positive effects regarding the evaporative phenomena and the change of the albedo of the roof. Therefore, it was decided to exclude a comparison with insulated roofs too, in accordance with existing literature studies—such as that by Niachou et al. [73]—demonstrating that the presence of green roof on an insulated roof is practically irrelevant.

5.4 Conclusions

The capability of green roofs in reducing the electric energy needs for the climatization of buildings and their environmental benefits has been extensively demonstrated in the literature.

The idea behind the presented work derived from considerations regarding the possible influence of green roofs on the indoor thermal comfort levels; that is, instead, an aspect often overlooked when estimating the performance of such building components. Therefore, the analysis methodology approach utilized (partly modelling and partly experimental) was implemented in light of such considerations.

Accurate knowledge of the internal temperatures of the ceiling is indeed an important prerequisite for establishing both achievable indoor comfort conditions and the energy demand for the air conditioning of the building itself. A lowering of the indoor temperatures in summer, and a rise during winter, lead, in fact to an improvement in the comfort levels for the occupants, and consequently, a saving on the use of the HVAC system, which, in turn, translates into a reduction of polluting emissions.

For this purpose, the comparison between Scenario #1 (where the monitored ceiling temperatures were used as boundary conditions) and Scenario #3 (standard roof case), and that between Scenario #2 (where the green roof configuration provided by EnergyPlus was utilized) and Scenario #3, allowed to prove how the presence of the experimental green roof on the monitored building improved the indoor comfort levels during summer by moderating the ceiling temperatures (Figures 5.9–5.11 and 13), despite some worsening during winter periods seeming to occur. Moreover, the temperature differences noticed had also a positive impact on the building energy consumption and the CO_2 emissions.

On the other hand, by comparing Scenario #1 with Scenario #2, it was possible to highlight the possible limits of the code's ability in adequately simulating the green roof behaviour. These limits are mainly represented by the lack of flexibility that EnergyPlus allows in the setting-process of some of the green roof physical parameters and in the way in which the code takes into account the solar radiation components.

Another aspect which should be better investigated, regards the PMV results (Figure 5.12). In fact, even though, also, in this case, a general positive effect due to the presence of the green roof can be seen, some criticalities emerged during some transition periods, for which the standard roof seems to perform slightly better than the green roof.

In conclusion, the proposed analysis made it possible to highlight how it is possible to assess the impact that green roofs have specifically on the indoor comfort levels, other than on the energy consumption.

Furthermore, the availability of field data put into evidence the importance of adequate simulation tools to facilitate the green roof design and assessment processes.

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SECTION I.A – Results and Findings

The outcomes of the studies reported in this section allowed to draw the following considerations.

- Regarding the use of innovative envelope components for retrofitting existing buildings, from the analysis of the proposed samples it emerged that:
  - specimens derived from homogeneous mixtures, where the inert natural material was finely grinded and blended into the paste of binder and water, show the most effective insulation features;
  - the most fibrous vegetal materials seem to performe better;
  - thermal conductivity tends to increase with the density of the sample;
  - the measured thermal conductivity values confirmed that the studied composites can be considered a practicable alternative to the mostly used traditional insulating materials.

- On the hygrothermal behavior of coconuts fiber insulators on green roofs the results showed that:
  - coconuts fiber and expanded polystyrene reached the same thermohygrometric performance, an important result since the first is a natural material whereas the second is a traditional synthetic one;
  - considering the dynamic energy behavior, coconuts fiber resulted in having a 1-hour greater time shift compared to the synthetic insulator.

- As for the analysis of the environmental impacts of an experimental green roof, by using the Life Cycle Assessment – LCA methodology, it arose that:
  - the phase which weighs more on the overall green roof life cycle analysis is the production one;
  - within the production total impact the water storage element represents the predominant component, followed by the drainage element, the substrate and finally the filter element.

- For what concerns covering the current gaps for an effective energy and environmental design of green roofs:
  - the cost for the disposal of an extensive green roof has only a slight incidence on its total life cycle cost (4%);

  - that the substrate is the greatest contributor to some impact categories such as Fresh Water Aquatic eco-toxicity (49%), Eutrophication (59%), and Acidification (46%);
  - significant errors (up to 45% in the case of heating and up to 24% in the case of cooling) in the estimation of thermal loads might occur when using generic data for the vegetation parameters of an extensive green roof;
  - as a comparative, a higher reduction of the climatization costs would result if installing cool paints or cool membranes on existing roofs instead of the adoption of green roofs.

- When considering green roofs as effective tools for improving the indoor comfort levels, it was possible to notice:
  - a general tendency to attain lower temperatures when the green coverage is higher;
  - the positive influence of the leaf area index – LAI on the green roof thermal behaviour;
  - how a light colour of the plants' leaf surface enabless a higher amount of solar radiation to be reflected;
  - contrary to the summer season, the presence of a green roof during the winter season does not seem to improve the indoor thermal conditions, while some criticalities emerged during some transition periods;
  - the use of EnergyPlus did not allow to set all the green roofs characteristic parameters freely, due to some constraints on the numerical values;
  - the advantage of using green roofs as a solution capable of achieving valuable energy savings (related to heating and cooling demands) and also a reductions of direct and indirect CO_2 emissions.

PART I – Interventions on Single Buildings

SECTION I.B – Lighting Systems: Energy and perception effects

This section presents the results of two experimental studies aimed at identifying and statistical analysing the relation between the specifics characterizing different types of LED (Light Emitting Diode) lamps and the human's organism reactions in terms of both visual and neurological (mainly, physiological and psycological) aspects. The idea at the base of this research subject stems from the importance that LED lighting has been gaining in recent years in the engineering/construction industry, being the one adopted in many standards and regulations concerning the reduction of lighting energy consumptions, which represent a significant share of the global amount of electricity usage. Hence, this section points out the relevance of also taking into account the occupants wellbeing when adopting a technology which allows the highest energy consumption reduction.
This section of the dissertation contains two chapters:

Chapter 6 - An experimental study on relationship between LED lamp characteristics and non-image-forming

Chapter 7 - Study of influence of the LED technologies on visual and subjectve/individual aspects

Chapter 6 - An experimental study on relationship between LED lamp characteristics and non image-forming

This chapter consists in the following conference paper, which derives from the undersigned PhD candidate's Masters Degree Thesis in Environmental Engineering:
La Gennusa, M., Macaluso, R., Mosca, M., Scaccianoce, G., Massaro, F., Cirrincione, L., An experimental study on relationship between LED lamp characteristics and non-image-forming, (2017) Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2017, art. no. 7977546.
DOI: https://doi.org/10.1109/eeeic.2017.7977546

Abstract: The general aim of the experimental study, presented in this paper, was that to investigate the relationship between the characteristics of five different types of LED (Light Emitting Diode) lamps, which are nowadays those allowing the highest energy consumption reduction, and the humans *non image–forming* (NIF) reactions.

Keywords: lighting; circadian system; led lamps; lighting color.

6.1 Introduction

One of the main goals in the engineering/construction industry is the reduction of lighting energy consumptions, which represent a significant share of the global amount of electricity consumptions.
That is why a key component of the EU energy policy, in recent years, has been that to promote the end-use energy efficiency in lighting, which also contributes to the reduction of carbon dioxide emissions, as part of the efforts to mitigate climate change. To this purpose several energy regulations and labelling systems have been implemented, based on reducing energy consumptions and verifying the compliance with standards related to the performance of visual tasks (such as the UNI EN 12464-1) [1-3].
One of the most efficient solutions available, at the moment, to improve lighting energy efficiency, and to reduce CO_2 emissions, is represented by LED (Light Emitting Diode) lighting; furthermore, LEDs high luminous efficacy level (lm/W), mercury free content, and long lifetime are some of the most important added values of this technology, in comparison to other light source technologies. As a result, LED

lamps efficacy and luminous characteristics have been improving very rapidly over the last few years, representing a valid retrofit solution, other than for the most common applications where white light is used, also for those sectors where efficient coloured light is required [1, 2].

However, another element that must be taken into account, concerning visual comfort, is the so called *non image-forming* (NIF) or "non-visual responses" to light. In fact several researches, carried out in the last few years, have shown that light (and its color) have a strong impact on humans health and wellbeing, affecting aspects that are not solely linked to vision, such as the perception of an environment, mood, and, more importantly the circadian system.

The latter is a biological clock that controls several processes, such as hormones production (melatonin in particular), brain wave patterns, body temperature, heart rate trends and many others. The basic parameters that affect circadian rhythms in terms of light are: timing and duration of exposure, intensity and, most importantly, spectral power distribution (SPD) of the light source [4-7].

Those aspects, and the mode of interaction between them and the biological clock, represent an important research field that need to be further investigated (and it currently is), in order to properly be integrated in future regulations and lighting design criteria.

This paper reports the results of an experiment carried out in order to investigate the link between the different, above-mentioned, impacts that light has on the human organism, by exposing a sample of 20 people to the 5 different types of LED lamps.

6.2 Methodology

The first step of the study consisted in testing the 5 LED lamps (used in the experiment) in laboratory using a spectrometer, in order to better define their luminous characteristics and also calculate the circadian stimulus *(CS)* values.

Subsequently an ad hoc light assessment questionnaire (Table 6.1), divided into different sections regarding photometry, colorimetry and psychological and physiological aspects, has been prepared to be used in the experiment; the questionnaire evaluation scale (chosen for this study) is shown in Table 6.2. A pre-questionnaire section was also included to try to establish the emotional state before the actual light assessment, in order to find a possible link between such emotional state and the way that the light is perceived.

Next, during the experimental phase, the participating subjects were exposed to each lamp (Fig. 6.1) every-night, for a week, for at least one hour before going to sleep. After every exposure they were asked to answer to the questionnaire.

Table 6.1. Questionnaire used in the experimental study.

Ambit		PRE - QUESTIONNAIRE	Label
EMOTIONAL STATE BEFORE THE ASSESSMENT		I feel nervous/stressed	EMO1
		I feel calm/relaxed	EMO2
		I feel tired (physically)	EMO3
		I ate heavy food	EMO4
		I ate too much (stomach heaviness)	EMO5
		LIGHTING ASSESSMENT QUESTIONNAIRE	
LIGHT VISUAL ASPECTS / PHOTOMETRY		The lighting is pleasant	VIS1
		The lighting is too bright	VIS2
		The lighting is too low/dim	VIS3
		The lighting is too warm (yellowish)	VIS4
		The lighting is too cold (bluish)	VIS5
		The lighting is natural	VIS6
		The lighting color allows me to carry out my task/activity	VIS7
COLOR RENDERING / COLORIMETRY		The lighting makes the colors and objects in the room appear bright	COL1
		The lighting makes the colors and objects in the room appear dark	COL2
		The lighting makes the colors and objects in the room appear intense	COL3
		The lighting makes the colors and objects in the room appear soft/weak	COL4
		The lighting makes the colors and objects in the room appear colored	COL5
		The lighting makes the colors and objects in the room appear uncolored	COL6
PSYCHOLOGIC. ASPECTS		I like the lighting	PSY1
		The lighting is comfortable	PSY2
		The lighting makes me feel calm/relaxed	PSY3
		The lighting makes me feel active/excited	PSY4
		The lighting makes me feel sleepy	PSY5
		The lighting makes me feel wide awake/alert	PSY6
PHYSIOL. ASP. (CIRCADIAN)	VISUAL COMFORT	The lighting causes me eye strain/fatigue	PHYLGT1
		The lighting causes me eye dryness	PHYLGT2
		The lighting causes me burning eyes	PHYLGT3
		The lighting causes me blurred/double vision	PHYLGT4
		The lighting causes me headache	PHYLGT5
	SLEEP QUALITY	My sleep was restful (I slept well)	PHYSLP1
		My sleep was restless (I slept badly)	PHYSLP2
		I fell asleep easily	PHYSLP3
		I've woken up during the night	PHYSLP4
		I've had nightmares	PHYSLP5
		I felt rested during the day	PHYSLP6

Table 6.2. Evaluation scale used in the questionnaire.

strongly agree	agree	somewhat agree	neutral	somewhat disagree	disagree	strongly disagree
3	2	1	0	-1	-2	-3

Figure 6.1. Lamps sequence used in the experimental study.

To avoid that the assessment on the lamps could influence each other, it has been chosen an appropriate sequence of alternation of the lamps, so as to have very different types of light in succession; therefore, it was used the following order: cold white, red, neutral white, blue, warm white (Fig. 6.1).

To obtain representative final values, as usually done when statistically treating data coming from a group of individuals answering a test, it was decided to proceed as follows:

- at the end of each week, hence relatively to the exposure to each of the 5 lamps, it was first calculated the weekly mean of the daily answers to the same question, for each subject, so as to obtain, for each answer to the question, a weekly representative assessment value $m_{j,k}$:

$$m_{j,k} = \frac{1}{n}\sum_{i=1}^{n} x_{i,j,k} \tag{6.1}$$

where:

  - $x_{i,j,k}$ is the value given to the answer, in the evaluation scale (Table 6.2);
  - n is the number of answers to each question, which is 7, one answer for each day of the week;
  - j is the question (going from 1 to 36);
  - k is the subject (going from 1 to 20).

- the mean values ($m_{j,k}$) were then further averaged, for each specific lamp, in order to obtain an overall evaluation, M_j, for each of the questionnaire answer relative to the lamp in question:

$$M_j = \frac{1}{N}\sum_{k=1}^{N} m_{j,k} \tag{6.2}$$

where:

  - $m_{j,k}$ is the mean relative to each of the questionnaires answer;

- *N* is the number of answers to each question, which is equal to 20, one for each test subject.

6.3 Analysis

6.3.A Lighting Sources Characterization

The commercial specifics of the 5 different types of LED lamps used in the experimental study are reported in Table 6.3, while the luminous characteristics of interest for this study (Table 6.4 and Figures 6.2 – 6.5), i.e. color values, CIE diagrams, and, most importantly, SPDs (as intensity of the luminous source plotted as a function of wavelength), were measured by testing them in the UNIPA DEIM laboratory TFL (Thin Films Laboratory) using the spectrometer "OceanOptics HR4000CG-UV-NIR" [8].

The instrument used a number of pixels in the processed spectrum of 3648 for every measure, while the integration time was changed in order to adapt to the specifics of each lamp, in particular: 200000 µsec for the white LEDs, 300000 µsec for the red one and 1000000 µsec for the blue one. The measured characteristics were simultaneously visualized on a computer with the proprietary software "OceanOptics SpecraSuite".

Table 6.3. Commercial specifics of the LED lamps.

Lexman led light bulb (spherical) specifics					
Light color	**Joint**	**Wattage (W)**	**Lum. flux (lm)**	**Glass Finishing**	**CCT (K)**
Cold white (C)	E14	3.5	250	frosted	6500
Neutral white (N)	E14	3.5	250	frosted	4000
Warm white (W)	E14	3.5	250	frosted	3000
Blue (B)	E14	2.5	249	frosted	-
Red (R)	E14	2.5	249	frosted	-

Table 6.4. Color values measured in laboratory.

Main characteristics measured in laboratory.		**Cold white**	**Neutr. white**	**Warm white**	**Blue**	**Red**
Tristimulus values	X	8436.9	9662.7	10454	1247.4	3161.7
	Y	9875.9	10244	10123	1425.5	1782.5
	Z	7513.0	5627.9	3481.7	3529.7	613.5
Chromaticity coordinates	x	0.3267	0.3784	0.4345	0.2011	0.5689
	y	0.3824	0.4012	0.4208	0.2298	0.3207
	z	0.2909	0.2204	0.1447	0.5691	0.1104

Color-Rendering Index CRI	76.3	80.2	80.4	-19.9	62.3
Correlated color temperature CCT (K)	5726	4214	3180	1625	1625
Dominant wavelength (mm)	493.9	491.9	511.2	484	760.4
Blue peak wavelength (mm)	454.2	454.2	452.1	451.3	-
Green peak wavelength (mm)	535.6	566.9	566.9	500.3	-
Yellow peak wavelength (mm)	574.7	589.3	595.5	-	-
Red peak wavelength (mm)	630.9	630.2	630.7	-	628.4

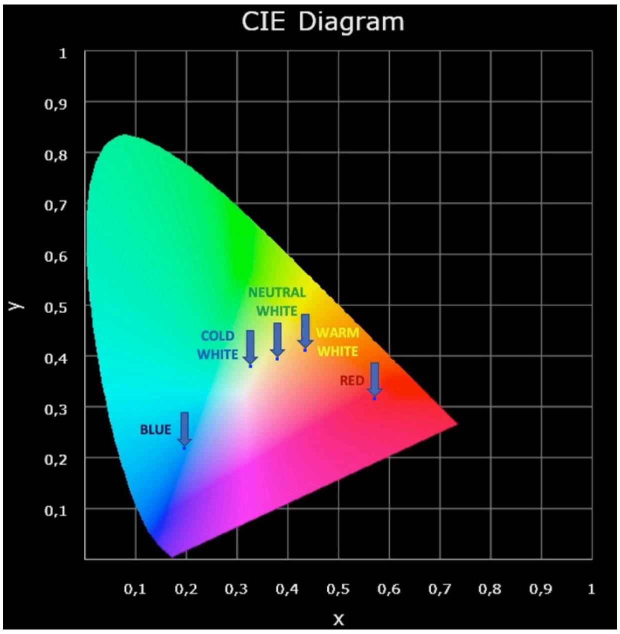

Figure 6.2. Characteristic points of the LED lamps plotted on the CIE diagram.

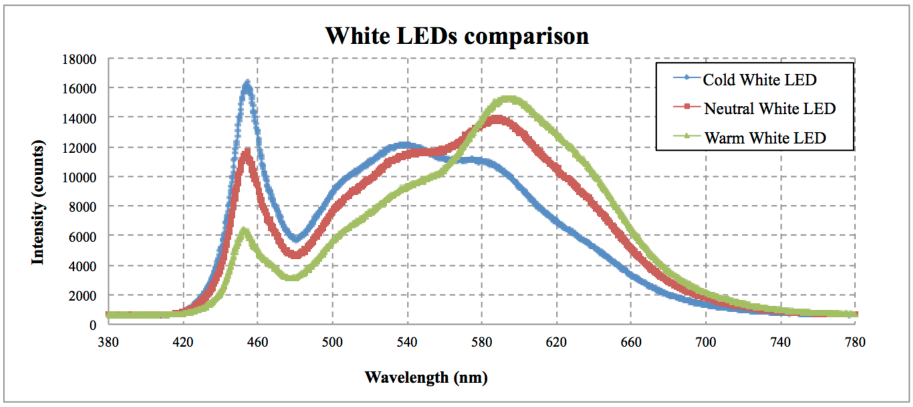

Figure 6.3. White LED lamps SPDs.

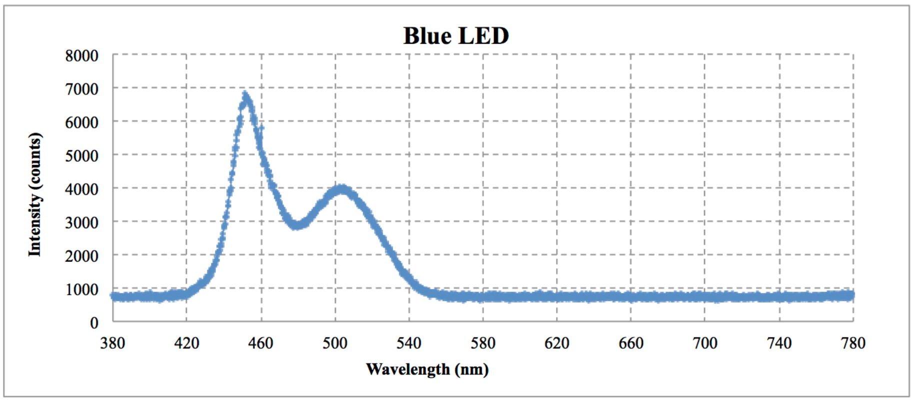

Figure 6.4. Blue LED lamp SPD.

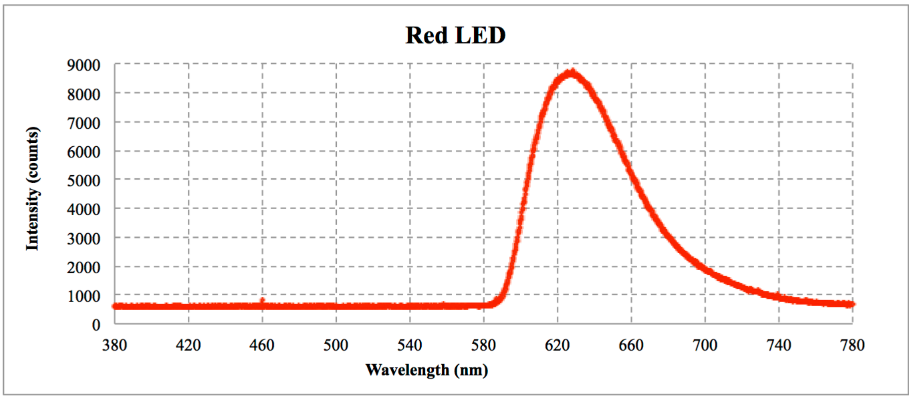

Figure 6.5. Red LED lamp SPD.

6.3.B Questionnaire Survey Campaign

Twenty selected individuals of age comprised between 18 and 62 (mean age 32), participated in the experiment, 11 males and 9 females.

Before starting the experiment, they all participated to a debriefing session, where the experiment, the questionnaire structure and the basics about light and color perception and attributes were explained, in order to familiarize with such concepts. All subjects were healthy during the execution of the experiment; moreover to avoid damage to the eye, a distance of 0.80 m between the lamp and the standing point of the subject during the experiment was chosen.

6.3.C Questionnaire Results

To obtain final results, representative of the link between LED lamp characteristics and NIF, the answers given by the subjects to each question were (as previously explained) averaged and analyzed. Figures 6.6 – 6.10 report the obtained final results for each question (see label reported in Table 6.1), one figure for each set of questions, where light blue represents the cold white lamp, green represent neutral white lamp, yellow represent warm white lamp and dark blue and red represent, respectively, the blue and the red lamps.

Regarding the *light visual aspects* (Fig. 6.6), it can be noted that the warm white lamp was the most appreciated one, instead the cold white one was the one considered too bright. The neutral white lamp was actually the one returning the color in the more natural way, while, as expected, the blue and red lamps have proven to be the most negatively evaluated under this point of view. As regard to the blue lamp, however, it must be noted that it was initially perceived as extremely low from all the subjects, but after a few days, probably due to the eye adaptation to the light, it was perceived as less dark than during the first days.

By analyzing the answers about the *color rendering aspects* (Fig. 6.7), the most positive judgments are those concerning the warm white and the neutral white lamps, the latter being the preferred one for brightness, although it makes the color appear more intense than they actually are; while the warm white lamp behaves slightly better under this aspect. As it could have been expected the blue and red lamps were less suitable in terms of color rendering. In fact, as can be seen in Fig. 6.7, the answers attributed to the blue and red lamps have an opposite trend compared to those regarding the white lamps.

Looking at the light *psychological aspects* (Fig. 6.8), the warm white lamp was, also in this case, the preferred one, and, together with the blue one, they are those giving the greater feeling of relaxation. The blue lamp was also found to be the one visually causing sleepiness, contrary to the cold white lamp, which instead appears to give more a state of alert.

Regarding the *visual comfort* (Fig. 6.9) conditions (part of the physiological aspects that affect the circadian system), it can be noted as actually no lamp seems to have a negative impact, even if the cold white one resulted as the most "annoying" amongst the five lamps. Another physiological aspect closely linked to the circadian system is the one concerning the *sleep quality* (Fig. 6.10), in this case it can be seen how none of the lamps caused problems such as poor sleep quality, nocturnal awakenings or nightmares. However, it can be noted how the blue lamp, contrary to that warm white one, proved to be the one connected to a lower rested feeling during the day after the exposure, actually much lower compared to all the other lamps. And it is also the one connected to lower values regarding the restful feeling associated to the sleep.

A link between the *emotional state before the assessment* and the way that the light is perceived was not found, hence the answer to that section of the questionnaire have not be included in the final results.

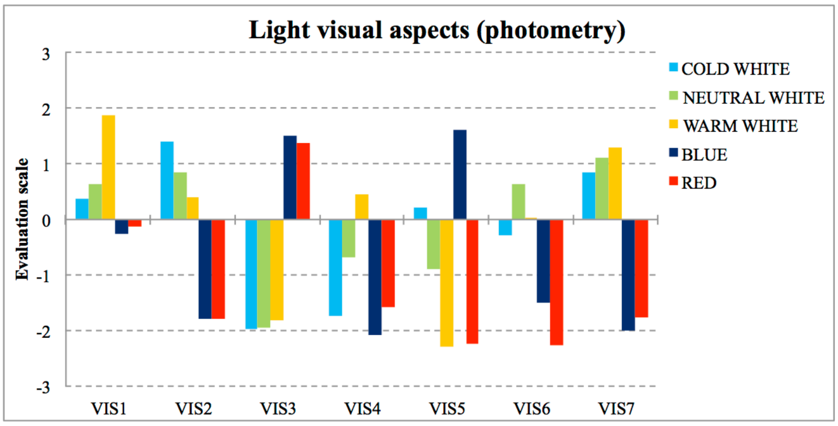

Figure 6.6. Light visual aspects (photometry) final results.

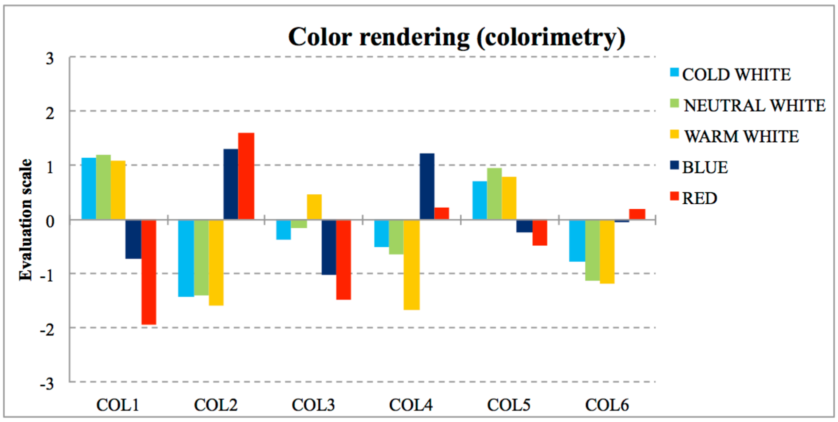

Figure 6.7. Color rendering aspects (colorimetry) final results.

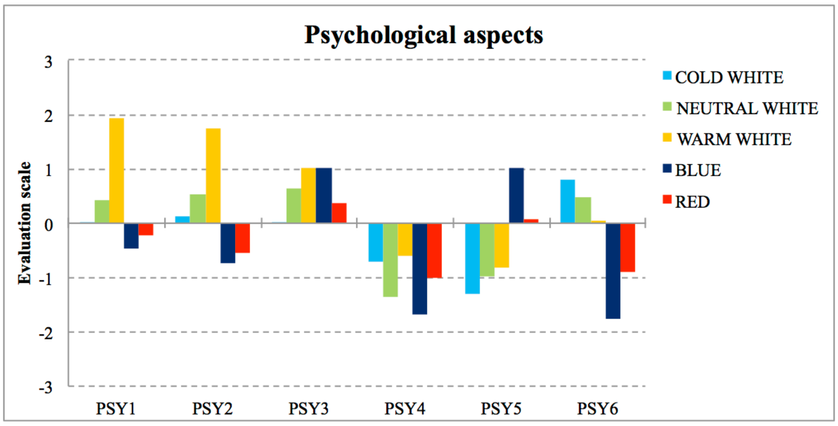

Figure 6.8. Psychological aspects final results.

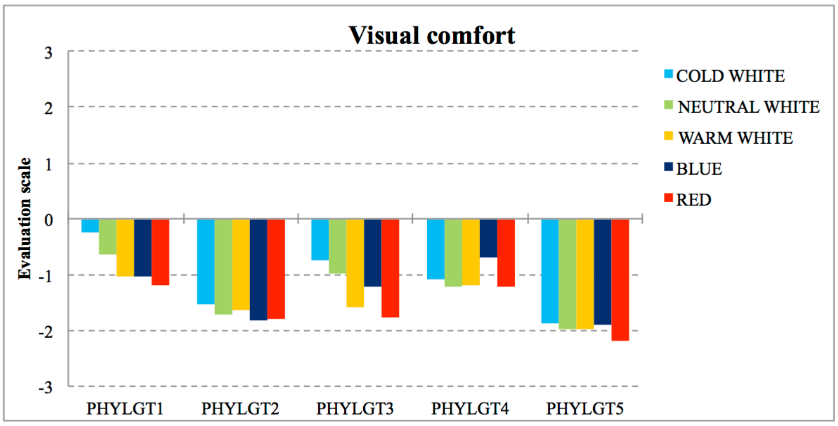

Figure 6.9. Visual comfort (physiological aspects – circadian) final results.

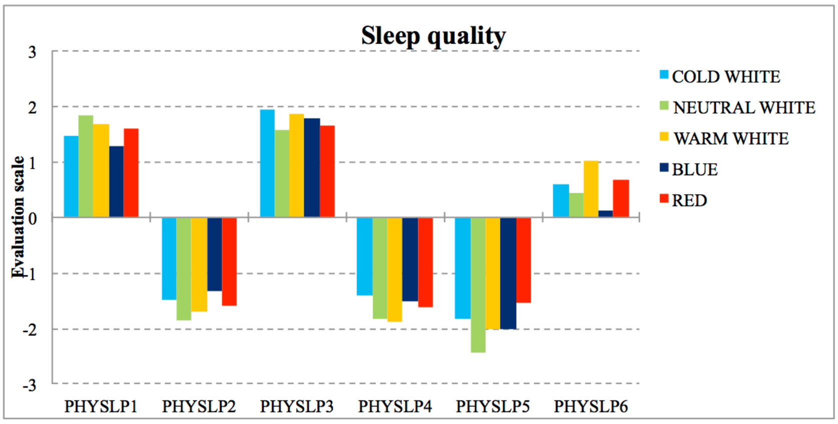

Figure 6.10. Sleep quality (physiological aspects – circadian) final results.

6.3.D Circadian Stimulus Calculation

Numerous mathematical models, called circadian phototransduction models, have been proposed to describe the interaction between light source and circadian system response [5, 9]. In this study it was used the model proposed by Rea *et al*., according to which the circadian efficacy depends on the light SPD at the eye [10, 11]. However, it was chosen to use, instead, the SPDs measured in laboratory, considering such approximation acceptable for this first investigation, given the proximity of the subjects to the lamps during exposure.

It was, thus, possible to calculate (6.3) the circadian stimulus (*CS*) values, as a percentage of a light stimulus, expressed in terms of nocturnal melatonin suppression, determined by an hour long exposure to light:

$$CS = 0.75 - \frac{0.75}{1 + \left(\frac{CL_A}{215.75}\right)^{0.864}} \tag{6.3}$$

It must be noted that *CS* is not a linear function of *CL_A*, ranging from a threshold value of 0.1 to a maximum (saturation) value of 0.75 (75%). CL_A being the circadian light, that is spectrally weighted irradiance for the circadian system, expressed in weighted W/m^2, calculated via (6.4) or (6.5):

$$CL_A = 1622\left[\int M_{C_\lambda} E_\lambda d\lambda + \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda\right) - \qquad a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{rodSat}}\right)\right)\right] \tag{6.4}$$

$$\text{if} \quad \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \geq 0$$

$$CL_A = 1622\int M_{C_\lambda} E_\lambda d\lambda \tag{6.5}$$

$$\text{if} \quad \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda < 0$$

where:

- $M_{C\lambda}$ is the melanospin sensitivity (corrected for criystalline lens transmittance);
- S_λ is the S cones sensitivity;
- mp_λ is the macular pigment transmittance;
- V_λ is the photopic luminous efficiency function;
- V'_λ is the scotopic luminous efficiency function;
- $rodSat = 6.5$ is the half-saturation constant for bleaching rods;
- $k = 0.2616$;
- $a_{b-y} = 0.6201$;
- $a_{rod} = 3.2347$;
- E_λ is the light source spectral irradiance (at eye level) function (W/m^2 nm);
- 1622 is a constant used to normalize CL_A so that a CL_A value of 1000 correspond to a 1000 lux and 2856 K blackbody radiation.

The results of the calculation are reported in Fig. 6.11 and Table 6.5.

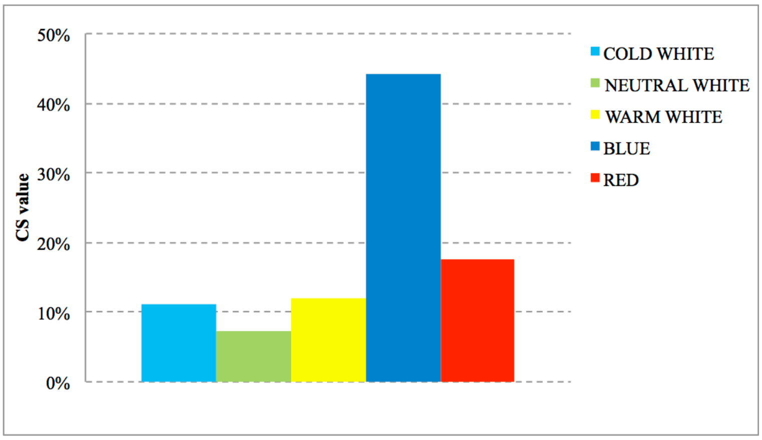

Figure 6.11. Circadian stimulus (CS) values, expressed in %.

Table 6.5. Results of the circadian stimulus calculation.

Light color	Spread angle	Dist. (m)	Illum. (lux)	CL$_A$ (weighted W/m^2)	Cs values
Cold white (C)	300°	0.8	33.317	29	0.112
Warm white (W)	300°	0.8	33.317	31	0.119
Neutral white (N)	300°	0.8	33.317	16	0.072
Blue (B)	150°	0.8	83.544	328	0.442
Red (R)	150°	0.8	83.544	54	0.175

6.4 Discussion

The experimental study has been successful in finding a correlation between the calculated *CS* values and the lighting quality assessment concerning *sleep quality* and *psychological aspects*, through the analysis of the trend obtained from the questionnaire answers. In fact, the greater *CS* value obtained was that of the blue LED lamp (Table 6.5, Fig. 6.11), corresponding to a greater melatonin suppression, and this aspect was indeed reflected by the answers to the assessment questionnaire section related to relax and sleep (Fig. 6.10).

As a matter of fact, although the blue lamp resulted being the one visually giving a greater feeling of sleepiness and relaxation (along with the warm white one, Fig. 6.6), it was actually the one causing a lower restful feeling associated to the sleep, and, above all, the lowest resting feeling during the day after the exposure, much lower than all the other lamps (Fig. 6.10); this shows an opposite trend between visual and circadian response to light.

Hence these aspects can be related to the impact of the melatonin suppression on the *circadian system*, so, to have a better sleep, it would be best to avoid exposure to blue light in the hours before bedtime.

The comparison between the questionnaire final results and the characterization of the lamps in laboratory also confirmed a correlation regarding the *light visual aspects* and the *color-rendering aspects*. In fact, the white LED lamps, characterized by a SPD spread more uniformly over the visible spectrum and higher CRI values (Table 6.4 and Fig. 6.2), received positive assessments, contrary to the blue and red ones, as could have been expected.

6.5 Conclusions

The general aim of the experimental study presented in this paper, was that to investigate the relationship between the characteristics of five different types of LED lamps (which are, nowadays, those allowing the highest energy consumption reduction) and the humans *non image–forming* reactions.

These reactions, in fact, manifest themselves mainly via the circadian rhythms, a series of biological processes regulated by the exposure to an alternation of light and dark conditions, and in particular by the SPD of the light source.

It must be noted that, due mainly to a still incomplete knowledge about how the circadian system exactly works, it has not been easy to develop the experimental structure used in the study to perform such evaluation. Nevertheless, the obtained final results still allowed to find such correlation.

In conclusion this experimental study represents the implementation of a procedure that could to be further developed and deepened in the future, possibly also integrating the medical aspects (e.g. saliva samples, of the subjects participating in the experiments, to measure the actual melatonin levels), to obtain a more complete assessment on the relationship between LED lamp characteristics and *non image-forming* reactions.

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Chapter 7 - Study of influence of the LED technologies on visual and subjective/individual aspects

This chapter consists in the following conference paper, which derives from the undersigned PhD candidate's Masters Degree Thesis in Environmental Engineering: Cirrincione, L., Macaluso, R., Mosca, M., Scaccianoce, G., Costanzo, S., Study of Influence of the LED Technologies on Visual and Subjective/Individual Aspects, (2018) Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018, art. no. 8494515.
DOI: https://doi.org/10.1109/eeeic.2018.8494515

Abstract: The general aim of this paper is that to further deepen and elaborate the results obtained in a previous study of the authors, in which the relationship between the characteristics of five different types of LED lamps and the humans *non-image-forming* reactions were investigated, by conducting a more detailed statistical analysis and by highlighting the neurological aspects.

Keywords: lighting; circadian system; led lamps; lighting color.

7.1 Introduction

In recent years one of the main goals in the lighting engineering field has been that to combine the reduction of lighting energy consumptions (which represent a significant share of the global amount of electricity consumptions) with the aspects regarding the comfortable performance of visual task as well as humans' health and wellbeing in terms of *non-image-forming (NIF)* or "non-visual responses" to light. These reactions manifest themselves mainly via the circadian rhythms, a series of biological processes (cell division, hormone production, sleep–wake cycles, cerebral cortex activity, body temperature, heart rate, etc.) regulated by the exposure to an alternation of light and dark conditions, and in particular by the spectral power distribution (SPD) of the light source.

Circadian rhythms, in fact, are governed by the *suprachiasmatic nuclei* (SCN), a network of control centers of the nervous system situated in the hypothalamus, which are affected by light through the *intrinsically photosensitive Retinal Ganglion Cells* (ipRGC), located mainly in the lower part of the retina. These cells are distinct from photoreceptors responsible for vision (rods and cones, located throughout the retina) and are most sensitive to the blue portion of the spectrum (centered around 460 *nm*), while the photopic spectrum is centered around 550 *nm.*

Presently, one of the most efficient solutions available, to improve lighting energy efficiency and to reduce CO_2 emissions, is represented by *Light Emitting Diodes* (*LEDs) technology*. Furthermore, LEDs high luminous efficacy level (lm/W), mercury free content, and long lifetime, are some of the most important added values of this technology, in comparison to other light source technologies. LEDs allow delivering substantial energy savings, up to 50% less energy than the fluorescent lamps, and may last 20 - 50 times longer than incandescent light bulbs and about 2 - 5 times longer than compact fluorescent lamps (CFLs). LEDs lifespan, indeed, ranges from 20000 to over 50000 hours, depending on the color, SPD and efficiency, against 10000 hours of a fluorescent lamp (and 1000 hours of an incandescent one). The only disadvantage may be the high initial investment cost, but that falls in a short time. In fact, LEDs have a luminous efficiency that typically ranges from 90 to over 100 lm/W, compared to 20 lm/W of CFL lamps.

Other than the most commonly used white LEDs, also applications where efficient colored light is required benefit nowadays from LEDs too, such as traffic lights and other signs. In fact, LEDs can easily achieve higher or lower CCTs than the conventional sources, which could satisfy both visual comfort preferences and/or improve working performances. Moreover, LEDs can be dimmed and this could be beneficial for lighting where dimming and integration with daylight is required, like in the case of indoor (offices, schools and residential) lighting [1, 2, 3, 4, 5, 6, 7, 8].

One of the characteristics that has a strong impact on LED lamps energy consumption is the lamp SPD, which, as previously reported, is also one of the basic parameters that affect the circadian rhythms in terms of light (the others being timing of exposure, duration of exposure, intensity of the stimulus, and exposure pattern to light). In fact, different studies have shown that light produced by LEDs is more efficient in the suppression of melatonin, which is a precise NIF response, than that produced by other lamps, having a SPD more similar to that of daylight than any other artificial lighting. This means that LEDs represent the best light source available, since their SPD contains all the wavelengths in the visible spectrum, and because our eyes have naturally adapted to them [9, 10, 11, 12, 13].

7.2 The Case Study

The aim of this paper is that to further deepen and elaborate the results obtained in a previous study of *La Gennusa et al.* (2017) [14], in which the relationship between the characteristics of five different types of LED lamps and the humans' *non-image–forming* reactions were investigated.

The study performed in [14] investigated the link between the lighting source and the different impacts that light has on the human body, by exposing a sample of 20 people to five different types of LED lamps (Table 7.1 and Figures 7.1 – 7.4), previously tested at the UNIPA DEIM laboratory with the "Ocean Optics HR4000CG-UV-NIR" spectrometer.

Table 7.1. Commercial specifics of the LED lamps.

Lexman led light bulb (spherical) specifics					
Light color	**Joint**	**Wattage (W)**	**Lum. flux (lm)**	**Glass Finishing**	**CCT (K)**
Cold white (C)	E14	3.5	250	frosted	6500
Neutral white (N)	E14	3.5	250	frosted	4000
Warm white (W)	E14	3.5	250	frosted	3000
Blue (B)	E14	2.5	249	frosted	-
Red (R)	E14	2.5	249	frosted	-

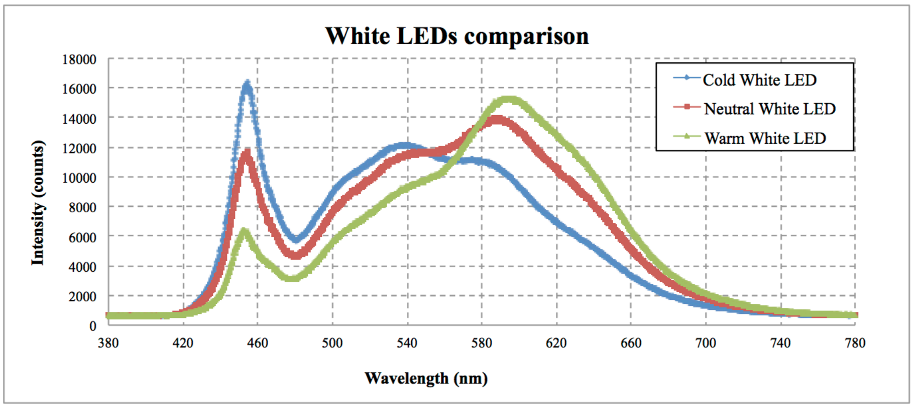

Figure 7.1. White LED lamps SPDs.

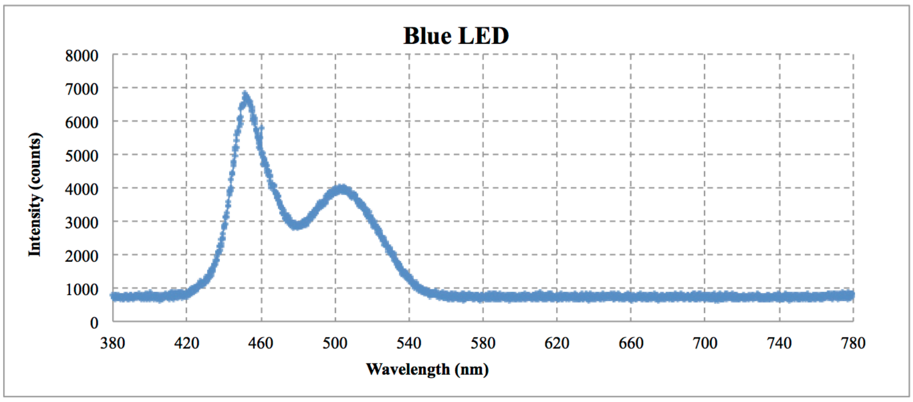

Figure 7.2. Blue LED lamp SPD.

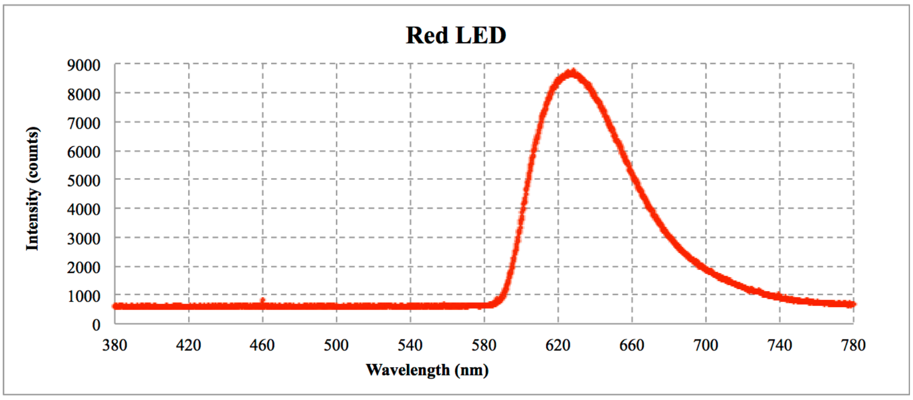

Figure 7.3. Red LED lamp SPD.

The subjects participating in the study were exposed to each lamp every day for a week for at least 45 minutes before going to sleep; successively to the exposure, they were asked to respond an ad hoc questionnaire (Tables 7.2 and 7.3), divided into the following sections: photometry (visual aspects of light), colorimetry (color rendering), psychological aspects, physiological aspects (circadian), the latter distinguished in visual comfort and quality of sleep.

To avoid that the assessment on the lamps could influence each other, it has been chosen an appropriate sequence of alternation of the lamps (Fig. 7.4), so as to have very different types of light in succession; therefore it was used the following order: cold white (C), red (R), neutral white (N), blue (B) and warm white (W).

Figure 7.4. Lamps used in the experimental study (from left to right: cold white, red, neutral white, blue, warm white).

Table 7.2. Questionnaire used in the experimental study.

	LIGHTING ASSESSMENT QUESTIONNAIRE	
LIGHT VISUAL ASPECTS / PHOTOMETRY	The lighting is pleasant	VIS1
	The lighting is too bright	VIS2
	The lighting is too low/dim	VIS3
	The lighting is too warm (yellowish)	VIS4
	The lighting is too cold (bluish)	VIS5
	The lighting is natural	VIS6

		The lighting color allows me to carry out my task/activity	VIS7
COLOR RENDERING / COLORIMETRY		The lighting makes the colors and objects in the room appear bright	COL1
		The lighting makes the colors and objects in the room appear dark	COL2
		The lighting makes the colors and objects in the room appear intense	COL3
		The lighting makes the colors and objects in the room appear soft/weak	COL4
		The lighting makes the colors and objects in the room appear colored	COL5
		The lighting makes the colors and objects in the room appear uncolored	COL6
PSYCHOLOGIC. ASPECTS		I like the lighting	PSY1
		The lighting is comfortable	PSY2
		The lighting makes me feel calm/relaxed	PSY3
		The lighting makes me feel active/excited	PSY4
		The lighting makes me feel sleepy	PSY5
		The lighting makes me feel wide awake/alert	PSY6
PHYSIOL. ASP. (CIRCADIAN)	VISUAL COMFORT	The lighting causes me eye strain/fatigue	PHYLGT1
		The lighting causes me eye dryness	PHYLGT2
		The lighting causes me burning eyes	PHYLGT3
		The lighting causes me blurred/double vision	PHYLGT4
		The lighting causes me headache	PHYLGT5
	SLEEP QUALITY	My sleep was restful (I slept well)	PHYSLP1
		My sleep was restless (I slept badly)	PHYSLP2
		I fell asleep easily	PHYSLP3
		I've woken up during the night	PHYSLP4
		I've had nightmares	PHYSLP5
		I felt rested during the day	PHYSLP6

Table 7.3. Evaluation scale used in the questionnaire.

strongly agree	agree	somewhat agree	neutral	somewhat disagree	disagree	strongly disagree
3	2	1	0	-1	-2	-3

Through the measures obtained in laboratory it was possible to calculate the circadian efficacy in terms of "circadian stimulus" (CS), calculated using the model proposed by *Rea et al.* [15, 16], according to which the circadian efficacy (in terms of melatonin suppression percentage) depends on the SPD of the light source (Fig. 7.5).

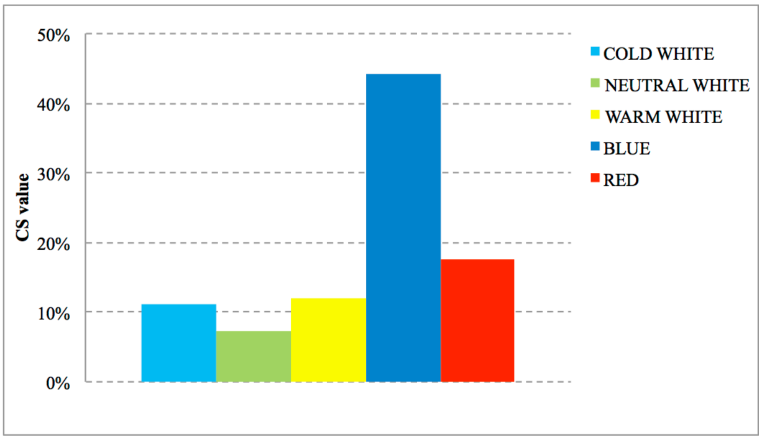

Figure 7.5. Circadian stimulus (CS) values, expressed in %.

7.3 Methodology

In this paper, as previously mentioned, in order to expand the findings of [14] (concerning the correlation between CS calculations and questionnaire results) a more detailed statistical study will be carried out and the neurological-medical aspects will be highlighted to obtain a more complete assessment on the relationship between LED lamps characteristics and *non-image-forming* reactions.

Given the numerosity of the collected data (i.e. the answers to the questionnaires) to perform the statistical analysis, the R© software developed by CRAN was used as support.

The first step consisted in testing the quality of the data collected by carrying out a χ-squared test, to check whether the differences between the answers given to the questionnaires during the experiments can be due to chance or actually have a statistical significance, setting significance levels comprised between 0.05 and 0.10.

To this end, some questions of the questionnaire were selected (i.e. those for which it was assumed that there was a certain correlation) and were divided into two types of couples:

- questions very similar to each other, for which a similar answers trend was expected;
- antithetical questions, for which an opposite answers trend was expected, and therefore can be considered as control questions.

The test was then carried out on the selected questions pairs, which confirmed the statistical significance of the collected data.

Subsequently, to measure the degree of correlation between the different questions, the Spearman correlation coefficients ρ_s were calculated. Given the sufficiently large sample size, to verify the significance of the obtained ρ_s values, the t Student's random variable was used (appropriately transforming the ρ_s values), which values were compared to the respective critical values by consulting the tables for different percentages of significance; considering, also in this case, significance levels comprised between 0.05 and 0.10.

Therefore, the correlations having a value of $\rho_s \geq 0.714$ were considered as significant, and it was hence possible to select the questions to analyze more thoroughly, namely: VIS1, VIS2, VIS4, COL1, COL5, PSY3, PHYLGT1, PHYLGT5, PHYSLP2.

In particular, the statistical in-depth analysis was carried out in order to obtain more detailed information about the answers frequencies, and their dispersion, by LED lamps.

7.4 Results and Discussion

For the questions concerning the *light visual aspects/photometry* section of the questionnaire, it was decided to show the graphs relative to the answers frequencies in the form of histograms, as they allow to better visually highlight what has been observed. In order to compare the different types of LED lamps (C, R, N, B, W) they are reported on the x-axis, while the different answers have been indicated with different colors.

For the question VIS1 (Fig. 7.6), a normal answer frequency distribution was found for the three white lamps, centered on the response 0 for the cold white, with a tendency of shifting to the left as the lamp's CCT decreases. The normal distribution indicates that the evaluation of the lamp does not tend to change with the passing of the days. While the red and the blue lamps histograms show a very similar and variable trend between the two extremes of the evaluation scale (going from 3 the first day to -3 the last day). This could indicate a certain dynamic of adaptation to these lamps.

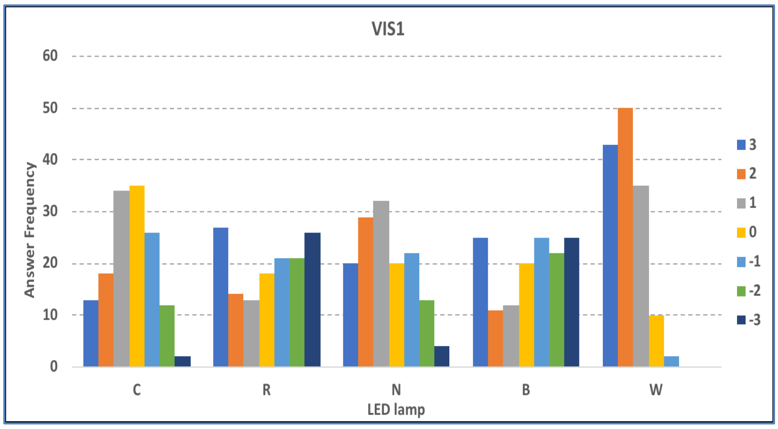

Figure 7.6. VIS1 (The lighting is pleasant) answer frequency distribution histograms.

Regarding the VIS2 question (Fig. 7.7), also in this case the white lamps show a normal answer frequency distribution, centered on 1 for the neutral and warm lamps and shifted to the left for the cold one. The red and blue lamps again are characterized by a very similar trend, tending to an exponential distribution, with the frequencies mainly concentrated in the negative part of the evaluation scale, with a maximum frequency of the answer -3. Such trend is usually indicative of a process in which events occur continuously and independently at a constant average rate, hence without an adaptation phase.

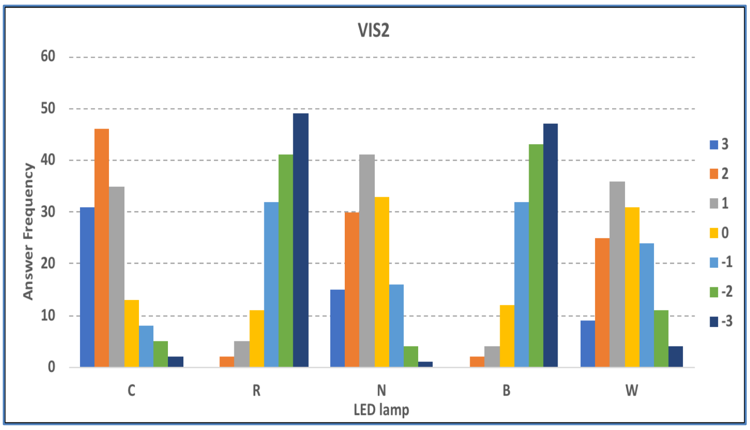

Figure 7.7. VIS2 (The lighting is too bright) answer frequency distribution histograms.

Looking at VIS4 histograms (Fig. 7.8) a normal answer frequency distribution for the white lamps is once again highlighted, centered on 1 for the warm white and with a tendency to shift to the right as the lamp's CCT increases. In this case the exponential trend of the distribution for the red and the blue lamps is even more evident, for which the same considerations made above are valid.

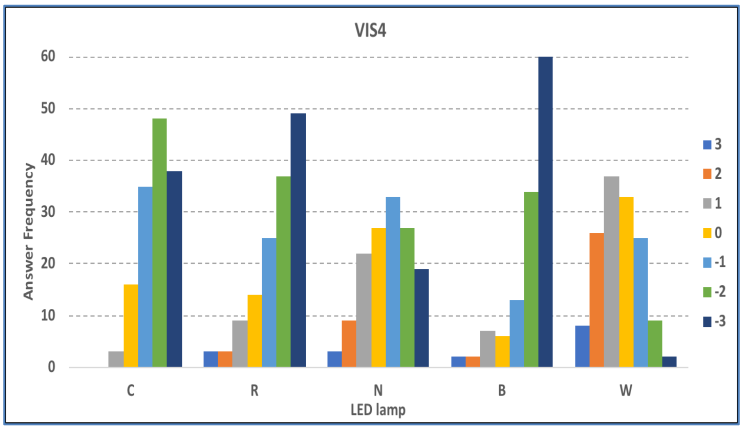

Figure 7.8. VIS4 (The lighting is too warm/yellowish) answer frequency distribution histograms.

For questions relative to the other sections of the questionnaire it was instead chosen to report the obtained results by using their boxplots, as in this case they give a more immediate visual representation. These graphs are in fact a good method to represent the distribution in a synthetic way, allowing to obtain information on the shape and symmetry of the answer frequency distribution. The whiskers also make it possible to highlight the presence of outliers.

For the COL1 and COL5questions (Fig. 7.9 and Fig. 7.10) the answer distributions appear symmetrical and have a rather narrow range for both the white lamps (centered on the value 1) and the red one (centered instead on the value -2). The evaluation of these lamps is therefore quiet sharp from a colorimetric point of view, while there is a much wider dispersion of the answers for the blue lamp (centered on the value -1), thus resulting the most unsettling color.

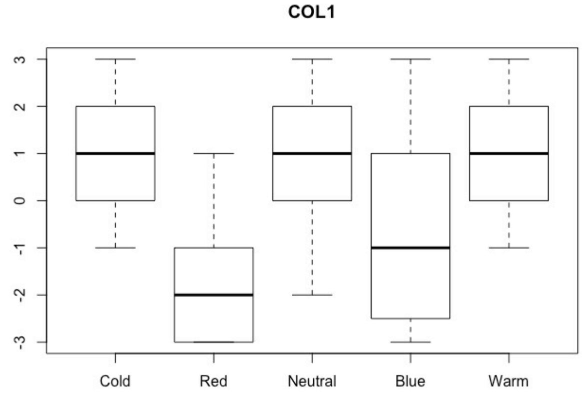

Figure 7.9. COL1 (The lighting makes the colors and objects in the room appear bright) boxplots.

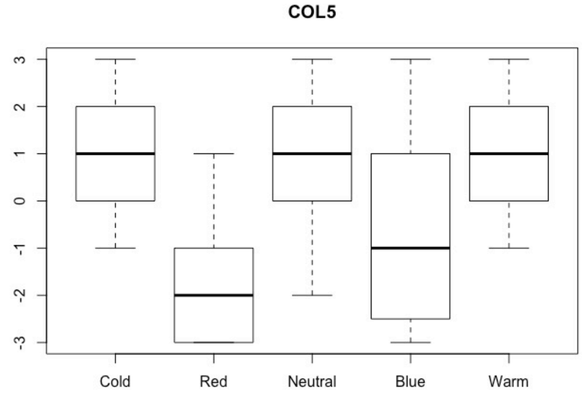

Figure 7.10. COL5 (The lighting makes the colors and objectsnin the room appear colored) boxplots.

The analysis of the PSY3 answers (Fig. 7.11) showed a rather limited dispersion of the values for the white lamps, with a symmetrical distribution for cold and warm ones (less symmetrical for neutral white). On the contrary there is a rather wide dispersion of values and an asymmetrical distribution for the red and the blue lamps, with trends that are opposite to each other. The blue lamp in particular resulted to be the most negatively evaluated, contrary to what could have been expected from the psychological point of view. In fact the immediate unconscious psychological reactions usually associated to the red color are those connected to a danger condition, while the blue is usually considered a color with a soothing effect, as also confirmed in [17].

As for the three white lamps their boxplots seem to confirm the fact that it is considered a neutral color.

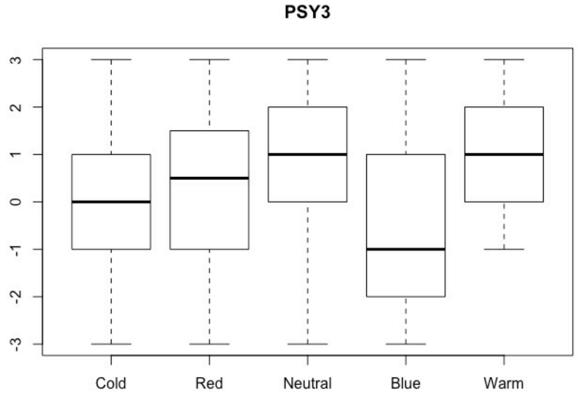

Figure 7.11. PSY3 (The lighting makes me feel calm/relaxed) boxplots.

Looking at the PHYLGT1 boxplots (Fig. 7.12) it can be noticed how the distributions of the cold white, neutral white and blue lamps have a more symmetrical shape and a more uniform dispersion. In particular that relating to the blue lamp is very reduced, although some outliers can be observed. The red and the warm white lamps show instead a greater dispersion and an asymmetric distribution (with opposite trends between the two lamps).

This aspect was investigated because the muscle structure physiological reactions are supposed to be different in relation not only to light, but also to its color. In fact, although no lamp seems to actually have caused eye strain/fatigue, the cold white one seems to be the more annoying, albeit there are outliers for the red and blue lamps, which show that in some cases these two lamps have also caused some problems.

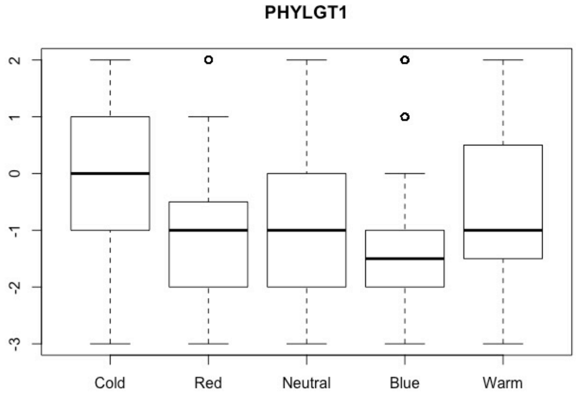

Figure 7.12. PHYLGT1 (The lighting causes me eye strain/fatigue) boxplots.

No lamp is associated with the presence of headaches, question PHYLGT5 (Fig. 7.13), though the warm\ lamp shows a wide dispersion, resulting in being the only one to be associated, in some cases, with affirmative answers. Which may confirm what seen in the PHYLGT1 boxplots, as eye strain and visual fatigue not only affects the ocular system, but they also have an impact on the brain, procuring headaches sensations.

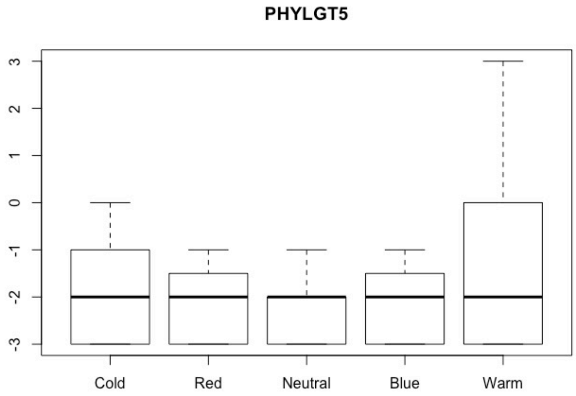

Figure 7.13. PHYLGT5 (The lighting causes me headache) boxplots.

The boxplots related to the question PHYSLP2 (Fig. 7.14) show how no lamp display a symmetrical distribution, however a greater dispersion has been found for the blue lamp (with a higher number of positive evaluations), which could confirm the results of the previous study [14].

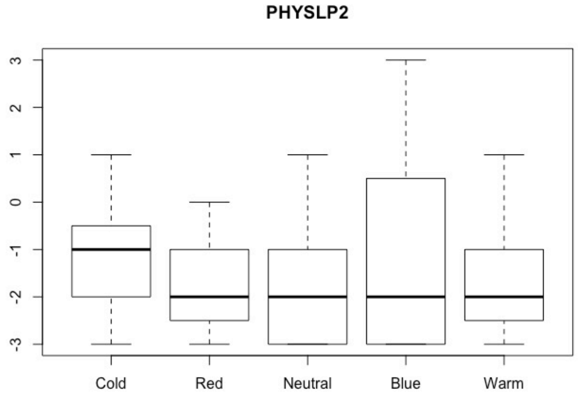

Figure 7.14. PHYSLP2 (My sleep was restless/I slept badly) boxplots.

The statistical in-depth analysis carried out in this paper allowed better defining some of the findings of the previous study [14]. In particular concerning the circadian aspect, the blue lamp has resulted being the more disturbing one, according to what was found by calculating the circadian stimulus (i.e. the blue light having an impact on the circadian system about three times greater than that generated by the white and red lamps as shown in Fig. 7.2).

Regarding the neurological aspects concerning the color perception, some observations can be made in particular for the red and the blue lamps. The obtained results, in fact, seem confirming the findings of previous studies (such as [17]) showing that color influences cognition and behavior through learned associations. In particular, red is often associated with danger and mistakes while blue is often associated with peace and tranquility feelings. Indeed people participating in the study before the experiment started expressed a general preference for blue against red color, although it was then found out that red seems to have a less negative impact on both visual and psycho-physiological aspects respect to blue.

Another interesting aspect to consider would be that concerning the different neurological perception of works of art due to different types of lighting. In terms of science certain feelings awaken from the sight of a painting result from the human's visual information processing, which is not only influenced by light and its colour, but also from the direction of the coming light (peripheral vision is just as important as central vision [18]).

7.5 Conclusions

In this paper a further detailed study of the results obtained in a previous work about the relationship between the characteristics of five different types of LED lamps (which are, nowadays, those allowing the highest energy consumption reduction) and the humans *non-image-forming* reactions was presented. In particular, a more detailed statistical analysis was conducted, and important neurological aspects were highlighted.

The statistical analysis has put in evidence some interesting aspects that were not highlighted in the previous study. In particular results showed that it is not easy to carry out an overall evaluation (i.e. considering all the questions in the questionnaire) for each type of LED lamp, as some aspects are opposite to each other. It would be more appropriate to change the evaluation point of view and switch to a demand-side perspective, which means identifying the type of lamp best suited to satisfy the specific requirements of the case in question.

Referring to the questionnaire used in this study, proceeding by project-objectives would therefore mean identifying the type of lamp that best meets the needs related to the different sections of the questionnaire. That is, in the case of light visual aspects (photometry), the most suitable light for the comfortable performance of the visual task, mainly useful for example in work and school environments. The section concerning colorimetry is instead more useful in those fields where the fundamental aspect is represented by the color rendering, such as museums and/or art galleries. While the parts concerning the psycho-physiological response to light, it can be exploited by professionals in the psychological, medical and neurological fields.

As for the purely neurological aspects, the statistical analysis did not allow to draw definitive conclusions, indeed the need to further develop this aspect emerged. It would be therefore useful to integrate the neurological findings of the study in the future with the support of experts in the neurological-medical field.

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SECTION I.B – Results and Findings

The main findings of this section can be summarized as follows:

- a correlation between the calculated circadian stimulus – *CS* values and the lighting quality assessment concerning *sleep quality* and *psychological aspects* was found, confirming the effectiveness of the calculation model;
- an opposite trend between visual and circadian response to light emerged;
- correspondence regarding the *light visual aspects* and the *color-rendering aspects* has been highlighted. That is, the white LED lamps, characterized by a spectral power distribution – SPD spread more uniformly over the visible spectrum and higher color rendering index – CRI values received positive assessments, contrary to the blue and red ones;
- the color of the light might influence cognition and behavior through learned associations.

The chapters presented in this section of the dissertation dealt with a subject that has been gaining much attention lately in both the engineering–physiological–psycological research fields, i.e. the possible effects that the adoption of a certain technology, primarly aimed at improving the occupants' wellbeing and obtaining the highest energy consumption reduction. Specifically, in this case the object in question has been the connection between LED - the most efficient solutions currently available in terms of lighting - and the *non image-forming* (NIF) - non-visual body responses - to light, which relevance has been internationally discussed in several recent and interesting studies.

It should be here pointed out that, given the novelty of this research topic, some difficulties arose during the design (setting up) and execution (performing) of this kind af experiments. In particular, the difficulties in involving a larger number of people in the analysis and the responsibility that this type of experimental study entails from a health point of view should not be underestimated, given that the effects are not yet well known (that is precisely the reason from which the investigation stems).

In light of these limitations, chapters 6 and 7 are to be interpreted as first initial investigations, conducted on a limited number of people to try to understand if they can be feasibly replicated on a larger scale, in order to potentially create in the future a task research on the topic concerning the relation among the NIF lighting aspects with those connected to the indoor visual comfort and the energy savings.

PART I – Interventions on Single Buildings

SECTION I.C – Renewable Energy Systems: The PV/T (photovoltaic-thermal) Case

This section focuses on the use of a particular Renewable Energy Source (RES), i.e. the photovoltaic-thermal (PV/T) system, as a viable solution able to integrate and/or replace (in certain contexts) the use of traditional fossil fuels, in order to reduce the environmental burden related to the production of thermal and electrical energy; such system, in fact, allows to produce both simultaneously. In particular, the influence that different system configurations of the thermal storage have on the electrical and thermal system performances were analysed.
This section of the dissertation is made up of one chapter:

Chapter 8 - Effect of the thermal storage dimensions on the performances of solar photovoltaic-thermal systems

Chapter 8 - Effect of the thermal storage dimensions on the performances of solar photovoltaic-thermal systems

This chapter consists in the following journal paper:

Cirrincione, L., Malara, C., Marino, C., Nucara, A., Peri, G., Pietrafesa, M., Effect of the thermal storage dimensions on the performances of solar photovoltaic-thermal system, (2020), Renewable Energy, 162, pp. 2004-2018.
DOI: https://doi.org/10.1016/j.renene.2020.09.140

Abstract: PV/T panels are innovative systems increasingly used in the building sector. As a matter of fact, in that context they allow a set of common problems to be addressed and often solved: lack of physical space and economic issues, always existing when PV and thermal panels are to be installed separately.

Obviously, the main objective of PV/T panels is to enhance the electrical efficiency by cooling the PV cells, but the side positive effect is also the production of thermal energy, which can be suitably exploited with a proper configuration of the whole system and an appropriate design of its components.

Their energy production and overall efficiency depend on several factors and therefore the effect of different system features should be investigated. In this work, a parametric analysis was performed to provide a contribution on this topic. The effects of the characteristics of the thermal storage on electrical and thermal system performances were analysed, also considering the influence of the thermal load magnitude.

The conclusive considerations can be exploited by designers and researchers to maximize the efficiency of the systems in relation to the storage tank characteristics and both electrical and thermal loads.

Keywords: Solar energy; Photovoltaic-thermal (PV/T) systems; Thermal storage.

8.1 Introduction

Nowadays, the energy policy of any country tries to address a plurality of issues such as energy security, economic growth and environment protection [1].

Considering these points of view, Renewable Energy Sources, appear to be a valid solution able to flank or, in particular situations, to substitute fossil fuels entirely. Actually, the renewable energy sources are used to supply only 14% of the world's total energy consumption [2]; likely, however, their role is bound to increase because of the rise in fossil fuel prices, global warming and planetary pollution issues.

Solar energy, among all other available energy resources, may be considered as the most abundant, inexhaustible and cleanest. Consequently, the installed area of solar technologies around the world is progressively increasing [3] with a remarkable pace, owing to the unlimited potential available in solar energy.

Many researchers around the world are developing systems based on solar energy [4,5]. The major applications of solar energy can be classified into two categories: solar thermal systems, which convert solar energy into thermal energy, and photovoltaic (PV) systems, which convert solar energy into electrical energy. These systems are usually used separately.

As regards PV cells, by and large, it is acknowledged that their output decreases when the operating temperature increases. Thus, in order to have a better performance, it is crucial to maintain the operating temperature values of the solar cells as low as possible [6,7], also considering the weather conditions of the site.

Therefore, in order to achieve a higher electrical efficiency, the PV module should be cooled by removing the heat, for instance exploiting the performance of a coupled solar air/water heater collector. The resulted combined system is called solar photovoltaic thermal (PV/T) collector and is able to produce thermal and electrical energy simultaneously. Apart from the twofold energy performance, the advantage of the PV/T system consists in the reduction of the demand of physical space as compared to the separated PV and solar thermal systems placed side-by-side.

These features make PV/T systems suitable for building installations, where the problem of limited usable shadow-free space on building rooftops is the key issue. Consequently, PV/T collectors are currently considered as a valid contribution to the actual implementation of the nearly Zero Energy Buildings (nZEB) concept [8-10].

A significant amount of theoretical [11,12] and experimental studies [13] on the PV/T systems has been carried out in the last few years, so that PV/T modules have been variously modelled [14,15]. The main purpose of these analyses was to explore the main factors influencing the electric and thermal performances of the systems.

As a matter of fact, albeit PV/T modules are cogenerating systems, producing both electric and thermal energy, hardly can their performances be optimized from all the functional perspectives (heat and electric energy conversion), so that, for the same operating conditions, single PV or thermal panels may be characterized by a higher efficiency in their correspondent function [16].

Within this framework, a remarkable number of the available studies focus on the PV/T features, with a view to analysing the influence of specific parameters [17] and designing efficient configurations [18-20] also depending on the used materials [21]. In addition, specific tools capable of simulating hybrid solar collectors were also devised [22,23].

Most of the cited studies, however, regard the panel specific features, constitutive materials and performances, without any reference to the structure or configuration of the plant, which they are usually part of.

As far as the integration of PV/T panels into plants and systems, the majority of research regards the analysis of specific configurations. For instance, a trigeneration system (PV/T plus absorption chiller) is analysed in Ref. [24] where a simulation tool was exploited to assess the energy savings for a specific case study with fixed loads. A sensitive analysis also demonstrated that for the studied case the results are dramatically sensitive to the variations of the PV/T area, whereas the other parameters (tank volume, fluid set point temperatures, and flow rate) slightly affect the overall results.

A case study with fixed loads (thermal and electric) was also considered in Ref. [25] where thermo-economic optimization of a specific solar system (for a specific range of design parameters involving the number of concentrated photovoltaic/thermal collectors, the number of PV collectors, the number of evacuated tube collectors, the volume of the storage tank, and the battery capacity) was performed.

The real buildings' energy demands of the University campus of Bari were also used as input to a transient system model in Ref. [26]. The system was a solar combined cooling, heating and power one based on hybrid PV/T modules. In the study, the water storage tank was modelled exploiting the same simulation procedure described in Ref. [27], where a temperature stratification was considered and an analysis regarding the influence of the storage volume on the energy and economic performance of a solar combined heat and power system was carried out. In this case, the specific electric and thermal loads of three reference buildings, each typical of three locations, characterized by diverse climate conditions, were used. The system components (e.g. number of modules, water tank volume, etc.) were dimensioned for each reference household.

To sum up, the majority of the available research refers to either the optimization of the PV/T module features and configurations or the analysis of the energy and economic performance of specific system structures, when called to meet specific loads also in different climate conditions. Therefore, an important contribution to the topic could be delivered by studies either addressing the issue of how the configuration and size of the system components may be arranged to meet different loads or aiming at the assessment of the thermal loads, which might be efficiently met by a specific system configuration.

In this context, the perspective of the proposed analysis regards the assessment of the thermal loads whose magnitude might be effectively satisfied by the proper system, depending on the water storage features, namely the tank size and thermal transmittance.

Specifically, the parametric analysis performed in this paper aims to provide indications about the effect of the combined interaction of the storage system features (size and thermal transmittance) and the thermal load magnitude on the temperature of the working fluid and, therefore, on the actual viability of the system.

The focus is also on the thermal losses from the storage tank and on the possibility of their exploitation to enhance the performance of the PV/T module, while preventing thermal storage temperature from dropping remarkably.

Therefore, the analysis is also devoted to the quality of the thermal energy attainable and not only to its global amount.

On the other hand, if a water temperature drop is inevitable in order to guarantee acceptable performances from the PV energy conversion point of view, the parametrical analysis reported in the presented article aims to single out the loads that could be better met in any of the examined cases.

These indications can be exploited by designers and researchers, to maximize the efficiency of the systems in relation to both the thermal load magnitude and the features of the water thank.

With a view to fulfilling the task, a simulation model was designed and implemented in a Visual Basic™ environment.

For the sake of simplicity, the model was designed with a view to maintaining a viability and an easiness of use, in order to possibly perform all the needed simulations swiftly, albeit keeping an acceptable level of accuracy, also considering that the focus of the analysis involves comparison purposes.

Several features of the system components were patterned and simulated in order to examine the effect of the characteristics of the thermal storage on both system's electrical and thermal performances; they vary for the thermal load magnitude and for both the thermal insulation properties and dimensions of the tank used for thermal storage purposes.

8.2 Methodology

The article presents the results of a parametric analysis focused on the assessment of the influence of both thermal storage features and thermal load size on the performance of photovoltaic-thermal systems, in order to single out the context and the constrains of their possible suitability.

Specifically, the aim is to investigate about the effect of the combined interaction of the storage system features (size and thermal transmittance) and the thermal load magnitude on the temperature of the working fluid and, therefore, on the actual suitability of the system.

From this perspective, as a matter of fact, the thermal losses might also be exploited with a view to striking a balance between the needs of improving both the photovoltaic conversion efficiency by cooling the PV module and the production of suitable thermal energy. In order to fulfil this task, the water storage tank should be designed properly.

The analysis proposed in the article focuses on this aspect of the issue, also regarding the quality of the produced thermal energy; to reach this aim, a simple model has been designed. It simulates the system behaviour in transient regime and is based on the lumped parameter model reported in Refs. [28], modified to take the effect of the PV module into account.

The steps of the whole procedure are synthetized in the flowchart of Fig. 8.1, and described in the following sections.

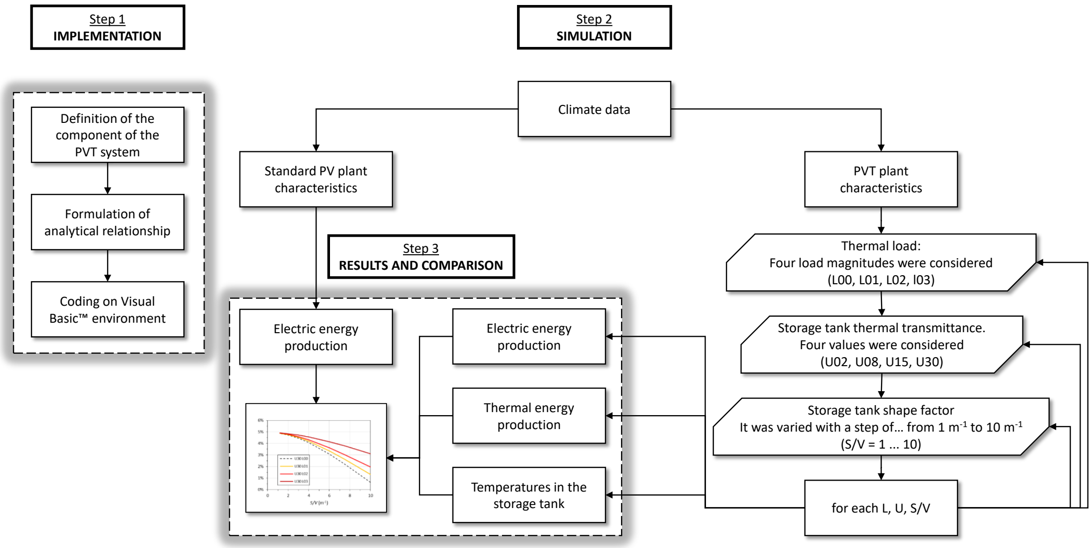


Figure 8.1. Flow-chart of the methodology.

Firstly, a pattern of a typical system was designed, considering the main constitutive elements (hybrid panels, pumps, thermal storage, expansion tank, etc, Fig. 8.2), and successively the plant operation was modelled by implementing, in a Visual Basic™ environment, proper relationships describing the various involved physical phenomena (e. g. photovoltaic conversion and heat exchanges) and their interaction.

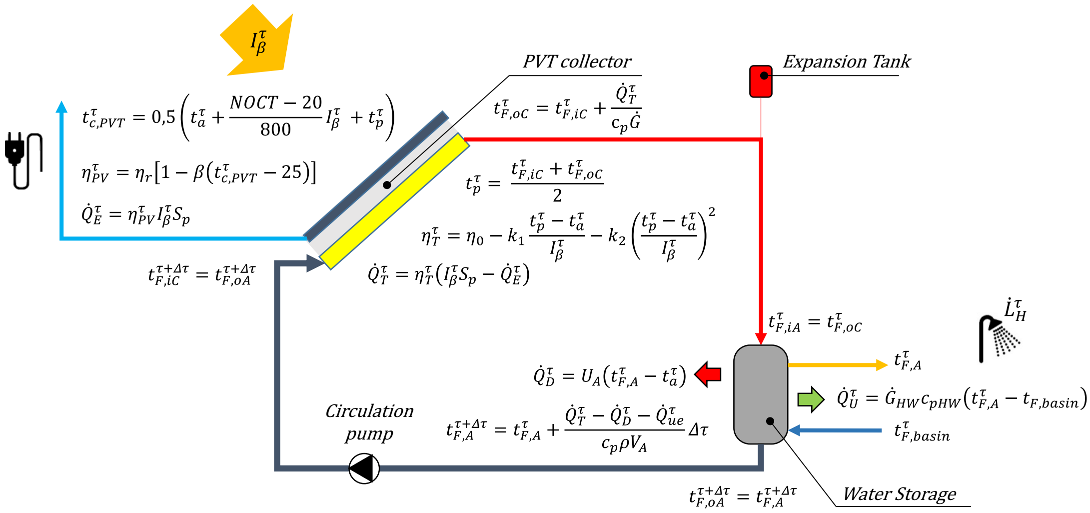


Figure 8.2. Scheme of the analysed system.

Several features of some system components were patterned and simulated; they vary for the thermal load size and for both the thermal insulation properties and dimensions of the tank used as thermal storage.

Discussed results regard both the yearly electric and thermal energy production, the water temperature of the thermal storage and the persistence of water temperature values suited to satisfy the thermal load requisites or, alternatively, to provide support to an auxiliary heating source.

In order to facilitate comparisons among outcomes of different systems configurations, all the energy amounts resulted from the simulations were referred to the annual electric energy production derived from a simple photovoltaic system working at the same conditions of the actual analysed plant. Specifically, the following indicators were evaluated:

- the ratio of the electrical energy production due to the use of the PV/T system respect to a standard PV one:

$$R_E = \frac{Q_{E,PV/T}}{Q_{E,PV}} \tag{8.1}$$

- the ratio of the thermal energy production to the electrical energy production of the standard PV system:

$$R_U = \frac{Q_U}{Q_{E,PV}} \tag{8.2}$$

- the increase of the electric energy production due to the use of the PV/T system with respect to a standard PV one:

$$\Delta_E = \frac{Q_{E,PV/T} - Q_{E,PV}}{Q_{E,PV}} \tag{8.3}$$

where:

- $Q_{E;\,PV/T}$ is the annual electrical energy, generated by the PVT panel (Wh);
- $Q_{E;\,\mathrm{PV}}$ is the annual electrical energy, generated by the PV panel characterized by the same features as the studied PV/T one and working at the same conditions (Wh);
- Q_U is the annual available thermal energy, at load disposal (Wh).

In addition, in order to sum up results regarding the energy production, the primary energy saving efficiency, hp, was also assessed. It is defined as [29]:

$$\eta_p = \frac{\eta_{PV}}{\eta_e} + \eta_T \tag{8.4}$$

where:

- η_{PV} is the efficiency of the PV panel;
- η_T is the thermal efficiency of the PV/T panel;
- η_e = 0:38 is the electrical power generation efficiency of the Italian energy system [30].

Furthermore, with a view to assessing the thermal conditions of the water storage, different parameters were considered: the maximum water temperature during the simulation period (one year), $t_{A,max}$, the fraction of time in a year during which the water temperature remains higher than 25 °C and 45 °C respectively, namely:

$$f_{25} = \frac{\tau(t_A > 25°C)}{8760} \tag{8.5}$$

$$f_{45} = \frac{\tau(t_A > 45°C)}{8760} \tag{8.6}$$

where $\tau(t_A > 25$ °C) is the length of the period of time during which the water storage temperature. t_A, is higher than 25 °C, whereas $\tau(t_A > 45$ °C). is the length of the period of time during which the water storage temperature t_A, is higher than 45 °C.

8.3 System modelling

The proposed simulation model is based on the lumped parameter model reported in Ref. [28], modified to take the effect of the PV section into account. It aims at simulating the system behaviour in transient regime.

The system has been patterned considering its main components: photovoltaic module, thermal collector and thermal energy storage system (Fig. 8.2).

The energy balance equation of the PV/T panel at time t is calculated assuming that the amount of solar radiation, which is not involved in the PV conversion, contributes to heating the cooling fluid:

$$\eta_T^\tau\left(I_\beta^\tau S_p - \eta_{PV}^\tau I_\beta^\tau S_p\right) = c_p \dot{G}\left(t_{F,oC}^\tau - t_{F,iC}^\tau\right) \tag{8.7}$$

where:

- η_T^τ is the thermal efficiency of the PV/T system;
- I_β^τ is the solar irradiance on the panel surface;
- S_p is the panel surface;
- η_{PV}^τ is the efficiency of the PV panel;
- c_p is the specific heat capacity;
- $\dot{G}$ is the water flow in the PV/T panel;
- $t_{F,oC}^\tau$ is the collector outlet water temperature;
- $t_{F,iC}^\tau$ is the collector inlet water temperature.

The thermal efficiency of the PV/T panel may be assessed as a function of the temperature of the absorber plate, t_p^τ, the air temperature, t_a^τ, and the solar irradiance [31]:

$$\eta_T^\tau = \eta_0 - k_1 \frac{t_p^\tau - t_a^\tau}{I_\beta^\tau} - k_2 \left(\frac{t_p^\tau - t_a^\tau}{I_\beta^\tau}\right)^2 \tag{8.8}$$

where η_0, $k_1$and k_2 are parameters characterizing the collector. The temperature of the absorber plate is assumed equal to:

$$t_p^\tau = \frac{t_{F,iC}^\tau + t_{F,oC}^\tau}{2} \tag{8.9}$$

where $t_{F,iC}^\tau$ e $t_{F,oC}^\tau$ are the collector inlet and outlet water temperature, respectively. The efficiency of the PV panel can be calculated by means of [31]:

$$\eta_{PV}^\tau = \eta_r\left[1 - \beta\left(t_{c,PVT}^\tau - 25\right)\right] \tag{8.10}$$

with η_r nominal efficiency of the PV panel, β temperature coefficient, and t_c^τ cell temperature.

Therefore, the performance of the system is a function of the cell temperature, $t_{c,PV/T}^\tau$, which in turn depends on both the cell temperature of the standard PV panel working at the same condition of the actual one, $t_{c,PV}^\tau$, and the thermal collector absorber plate temperature, t_p^τ. It was assumed that:

$$t_{c,PV/T}^\tau = \frac{t_{c,PV}^\tau + t_p^\tau}{2} \tag{8.11}$$

The assumption was motivated by the following considerations. The possible values of the cell temperature of the PV/T panel are restrained within a range whose limits are: $t_{c,PV}^\tau$ and t_p. For the higher inertia of the thermal component of the system (which exploits water as working fluid), it is more likely that the actual temperature of the cell, $t_{c,PV/T}^\tau$, is nearer to absorber temperature, t_p, than cell temperature of the simple PV panel. Nonetheless, as a conservative hypothesis from the perspective of electric production, an average value was considered.

The cell temperature of the standard PV system operating at the same condition of the actual PV/T plant, $t_{c,PV}$, is usually calculated by means of the well-known equation [32]:

$$t_{c,PV}^\tau = t_a^\tau + \frac{NOCT - 20}{800} I_\beta^\tau \tag{8.12}$$

where *NOCT* is the Nominal Operating Cell Temperature, t_a^τ the air temperature and I_β^τ the solar irradiance on the panel surface.

The collector outlet water temperature, $t_{F,uC}^\tau$, is hereafter calculated from eq. (8.7), by means of the following formula:

$$t_{F,oC}^{\tau} = t_{F,iC}^{\tau} + \frac{\dot{Q}_T^{\tau}}{c_p \dot{G}} \tag{8.13}$$

where:

$$\dot{Q}_T^{\tau} = \eta_T^{\tau}(I_\beta^{\tau} S_p - \dot{Q}_E^{\tau}) \tag{8.14}$$

and

$$\dot{Q}_E^{\tau} = \eta_{PV}^{\tau} I_\beta^{\tau} S_p \tag{8.15}$$

The water temperature in the storage system is calculated considering the following energy balance equation [33]:

$$c_p \rho V_A \frac{dt}{d\tau} d\tau = \dot{Q}_g d\tau - \dot{Q}_l d\tau \tag{8.16}$$

where ρ is the density of the fluid, V_A the storage volume, $\dot{Q}_g$ the energy supply flow, and $\dot{Q}_l$ indicates the thermal losses.

Under the hypothesis that the thermal losses within the water circuit are negligible and assuming that no fluid stratification occurs within the water tank, so that the storage temperature $t_{F,A}$ is uniform [28,33] (perfect mixing hypothesis), it results that:

$$t_{F,A}^{\tau+\Delta\tau} = t_{F,A}^{\tau} + \frac{\dot{Q}_T^{\tau} - \dot{Q}_D^{\tau} - \dot{Q}_{ue}^{\tau}}{c_p \rho V_A} \Delta\tau \tag{8.17}$$

where $\dot{Q}_D^{\tau}$ is the thermal flow through the envelope structure of the water storage, $\dot{Q}_{ue}^{\tau}$ is the thermal power sent to the thermal load, ρ is the density of the fluid, and V_A is the volume of the storage.

The hypothesis of negligible thermal losses implies that:

$$t_{F,oC}^{\tau} = t_{F,iA}^{\tau} \tag{8.18}$$

$$t_{F,oA}^{\tau} = t_{F,iC}^{\tau} \tag{8.19}$$

Therefore, the following equation may be yielded:

$$\dot{Q}_T^\tau = \dot{G}c_p\left(t_{F,oA}^\tau - t_{F,iA}^\tau\right) = \dot{G}c_p\left(t_{F,iC}^\tau - t_{F,oC}^\tau\right) \tag{8.20}$$

The thermal flow through the envelope structure of the water storage is calculated by:

$$\dot{Q}_D^\tau = U_A(t_{F,A}^\tau - t_a^\tau) \tag{8.21}$$

in which U_A is the thermal transmittance of the envelope structure of the water storage.

As regards the effective thermal power, $\dot{Q}_{ue}^\tau$, namely the thermal power, which is actually sent to the thermal load, it is calculated considering that, when the thermal energy production exceeds the thermal demand, only the needed portion of the global available thermal power $\dot{Q}_U$ is used to meet the thermal load $\dot{L}_H$.

Therefore:

$$\dot{Q}_U^\tau = \dot{G}_{HW}c_p(t_{F,A}^\tau - t_{F,basin}) \tag{8.22}$$

where $\dot{G}_{HW}$ is the water flowof the fluid in demand loop and $t_{F,basin}$ the groundwater temperature, and:

$$\begin{aligned} \dot{Q}_{ue}^\tau &= \dot{Q}_U^\tau \quad if \quad \dot{Q}_U^\tau \leq \dot{L}_H^\tau \\ \dot{Q}_{ue}^\tau &= \dot{L}_H^\tau \quad if \quad \dot{Q}_U^\tau > \dot{L}_H^\tau \end{aligned} \tag{8.23}$$

Moreover, it is assumed that:

$$\dot{Q}_{ue}^\tau = 0 \quad if \quad \dot{Q}_U^\tau < 0 \tag{8.24}$$

Finally, the collector inlet water temperature will be equal to the storage outlet water temperature:

$$t_{F,iC}^{\tau+\Delta\tau} = t_{F,oA}^{\tau+\Delta\tau} = t_{F,A}^{\tau+\Delta\tau} \tag{8.25}$$

The procedure was implemented in a spreadsheet, using VisualBasic™ function and macros, and a user-friendly interface was designed. The used time step is equal to 6 min (10 steps every hour).

At each time step, the climatic parameters, recorded on an hourly basis, were calculated by linear interpolation using the values corresponding to two consecutive hours.

The code output consists of:

- cell temperature $t_{c,PV/T}^{\tau}$;
- inlet and outlet water temperature of the collector, $t_{F,iC}^{\tau}$ and $t_{F,oC}^{\tau}$;
- water storage temperature $t_{F,A}^{\tau}$;
- generated electrical power $\dot{Q}_{E}^{\tau}$;
- generated thermal energy $\dot{Q}_{T}^{\tau}$;
- global available thermal power $\dot{Q}_{U}^{\tau}$;
- effective thermal power $\dot{Q}_{ue}^{\tau}$;
- thermal flow through the envelope structure of the water storage $\dot{Q}_{D}^{\tau}$;
- electrical efficiency η_{PV}^{τ} ;
- thermal efficiency η_{T}^{τ}.

8.4 Performed analysis

With the aim of analysing the role of thermal storage structure on the performances of the whole system, several configurations were patterned and simulated; they vary for the thermal load and for both the thermal insulation properties and dimensions of the tank used for thermal storage purposes.

8.4.1 Climate area

The studied PV/T system is located in Reggio Calabria, (38°07'12" North latitude, 15°40'12" East longitude), a town situated on the Southern coast of the Italian Peninsula and characterized by a typical Mediterranean climate profile, with mild winter climate and dry warm summer.

The needed climate data were obtained through a measurement campaign performed at the Mediterranean University campus. Solar radiation was measured by means of a Kipp and Zonen CNR4™ net radiometer, whereas the air temperaturewas measured using the Vaisala WXT 520 weather station. The technical characteristics of the measuring equipment are reported in Table 8.1 and Table 8.2. Weather data were measured with an hourly time step, for a whole year.

Table 8.1. Technical characteristics of CNR4™ net radiometer.

Measured parameter	Measurement range
Spectral range	300 - 2800 nm (50% points)
Sensitivity	10 to 20 μV/ (W/m²)
Response time	< 18 s (95% response)
Non-linearity	< 1 % (from 0 to 1000 W/m2 irradiance)
Tilt error	< 1 %
Field of view:	180°
Directional error:	< 20 W/m² (angles up to 80° with 1000 W/m² beam radiation)
Irradiance:	0 to 2000 W/m²
Uncertainty in daily total	< 5% (95 % confidence level)

Table 8.2. Technical characteristics of Vaisala WXT520.

Measured parameter	Measurement range	Accuracy
Air temperature	-52…+60°C	±0.3°C
Relative Humidity	0-100%	±3% RH
Rain intensity	0-200 mm/h	±0.1 mm/h

The climatic conditions of the site are synthetically depicted in Fig. 8.3, which reports the values of both the monthly solar radiation on the horizontal plane and the daily average air temperature, obtained from the measured data.

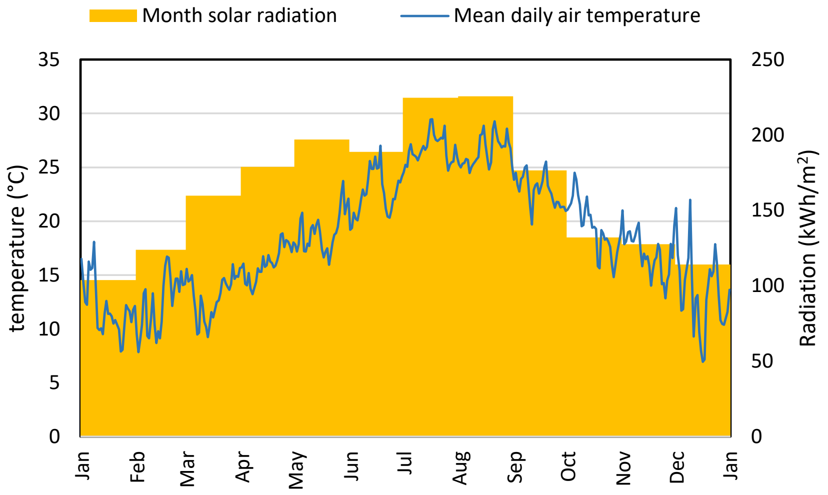


Figure 8.3. Monthly solar radiation on the horizontal plane and daily average air temperature.

These measured climatic data were used as input to the simulation model, which assesses the values of every parameter in correspondence of each calculation step (equal to 6 min) by means of the linear interpolation method.

In addition, the hourly components of the solar radiation shining on the PV/T panel surface were assessed by means of the Liu and Jordan method [34], starting from the knowledge of the measured hourly global solar radiation on the horizontal surface [35].

Measured data allowed the actual climate conditions of the site to be taken into account, especially as far as solar radiation is concerned [36].

8.4.2 Thermal load

Four constant thermal loads, L_H, were considered; their amounts are reported in Table 8.3.

Table 8.3. Thermal loads.

Load hypothesis		Yearly thermal energy demand, $L_{H,y}$ (kWh)	Instantaneous thermal load $L_{H,h}$ (W)
L00 →	$L_{H,y} = 0$	0	0
L01 →	$L_{H,y} = 0.5\ Q_{E,PV,y}$	136	15.5
L02 →	$L_{H,y} = Q_{E,PV,y}$	272	31
L03 →	$L_{H,y} = 2\ Q_{E,PV,y}$	543	62

Specifically, in Table 8.3, the yearly thermal demand $L_{H,y}$ is conveyed as a function of the yearly electric production, $Q_{E,PV}$, of the PV system working at the same conditions of the actual PV/T:

$$\boldsymbol{L_{H,y}} = Q_{E,PV,y} \times k \tag{8.26}$$

with $k = 0.0; 0.5; 1.0; 2.0$.

The value of $Q_{E,PV,y}$, assumed as reference, resulted from the simulation of a standard PV system with unitary panel surface.

The constant thermal power instantaneously requested by the load, $L_{H,h}$, was hence calculated by means of the following equation:

$$\boldsymbol{L_{H,h}} = \frac{\boldsymbol{L_{H,y}}}{8760} \tag{8.27}$$

The choice of using a constant thermal load profile only relies on the fact that former analyses [37] demonstrated that the result variability due to the thermal load profile (constant or variable) is real, but less significant than the one caused by variation in storage features such as transmittance and shape factor.

Moreover, the aim of the study is to compare the output yielded by different system feature configurations rather than determine an absolute value of energy production. From this perspective, the real issue is that the input data and initial conditions are equal for each simulated configuration.

8.4.3 PVT panel

The studied PV/T panel consists of a Monocristalline PV module and a sheet and tube absorber. The panel surface is 1 m^2, the electrical and thermal specifications of the system are reported in Table 8.4.

Table 8.4. PV/T panel technical features.

Electrical specifications			**Thermal specifications**		
η_r **(-)**	$NOCT$ **(°C)**	β **(%/°C)**	η_0 **(-)**	k_1 **(W/m^{2}K)**	k_2 **(W^2/m^{4}K^2)**
0.150	45.0	-0.4	0.500	4.58	0.00135

All the simulations regarded a panel with unitary surface, peak power of 120W/m^2, facing South and inclined at an angle of 28° to the horizontal plane.

Solar irradiance on the PV/T surface was calculated by means of the Liu and Jordan method [34], using the measured data on the horizontal plane.

8.4.4 Storage tank

With a view to evaluating the effect of the characteristics of the thermal storage, several insulation configurations of the tank were considered. The correspondent thermal transmittance values are reported in Table 8.5; moreover, the simulations were performed for various values of the shape factor, that is the ratio of the surface of the tank envelope, *S*, to its volume, *V*.

Table 8.5. Considered thermal transmittance values of the storage tank.

Case	**Thermal transmittance, U (W/m^{2}K)**
U30	3.0
U15	1.5
U08	0.8
U02	0.2

8.5 Results

Firstly, with a view to giving a preliminary information regarding the obtained results, Fig. 8.4 and Fig. 8.5 report the time trend of the water storage temperature, air temperature and solar radiation on the panel surface for a summer week and for a winter week, respectively. Similar results can be obtained for each involved parameter (e.g. cells and fluid temperatures, generated electric and thermal energy, electric and thermal efficiency, etc.).

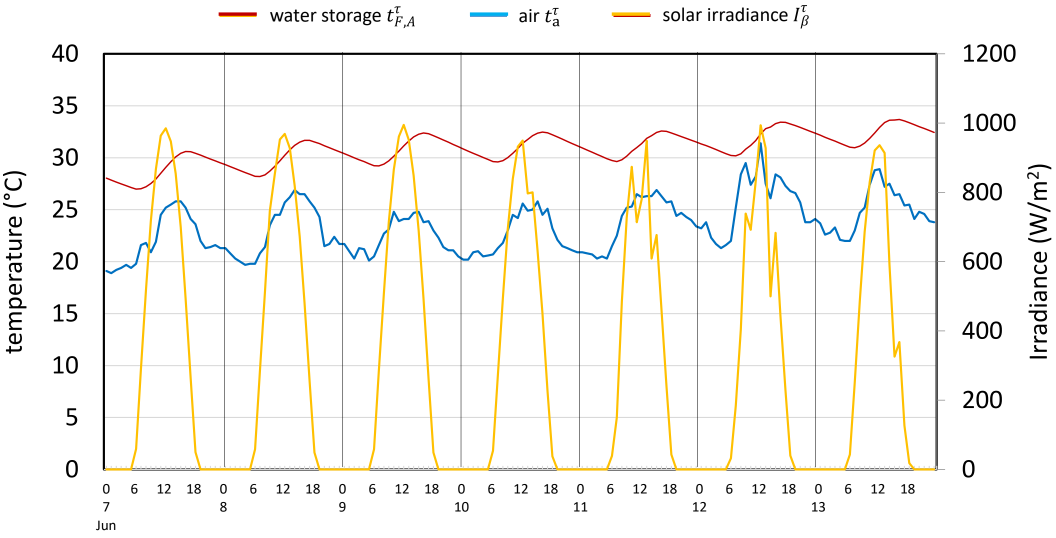


Figure 8.4. Time trend of water storage temperature, air temperature and solar radiation on the panel surface (summer week, $L_{H,h}$ = 31W, U = 3.0 W/m^2°C, S/V = 6.0m^{-1}).

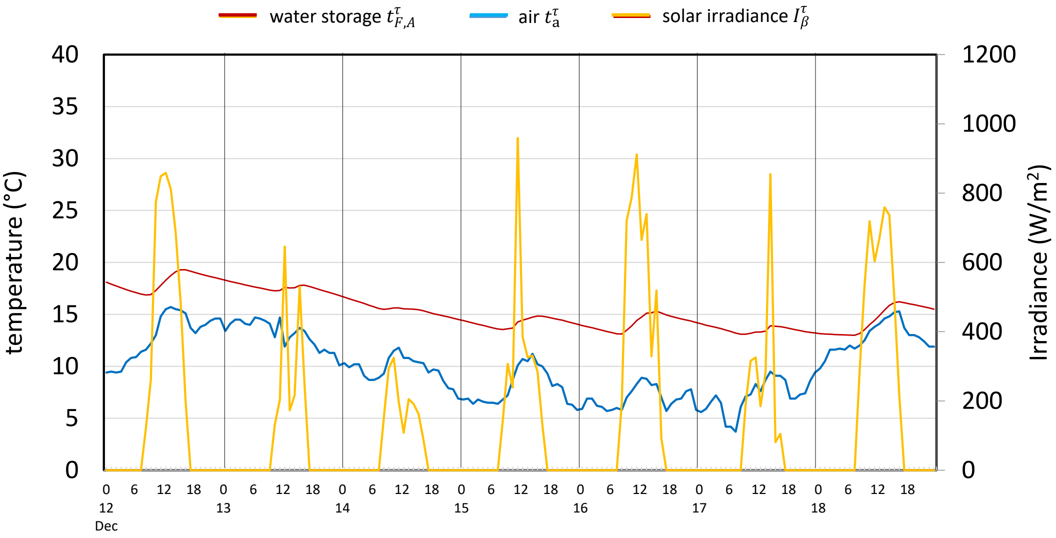


Figure 8.5. Time trend of water storage temperature, air temperature and solar radiation on the panel surface (winter week, $L_{H,h}$ = 31W, U = 3.0 W/m^2°C, S/V = 6.0m^{-1}).

Specifically, the trends depicted in the two figures refer to a specific case consisting of the following conditions:

- Load configuration L02, $L_{H,h}$ = 31W;
- Thermal transmittance U30, U = 3.0 W/m^2°C:
- Shape factor S/V = 6.0m^{-1}.

It can be noted that the water storage temperatures are lower than 35 °C also during the June week, and their trend follows the climatic condition variability (air temperature), with a thermal inertia whose effect is visible during the cooling phase starting after sunset; this is in accordance with other findings [26].

Obviously, Figs. 8.4 and 8.5, referring to a single case in a short period of time, can be considered only as an example of the system behaviour. In fact, they give no information regarding both the annual system performance and the effect of the change in the parameter values involved in the parametric analysis.

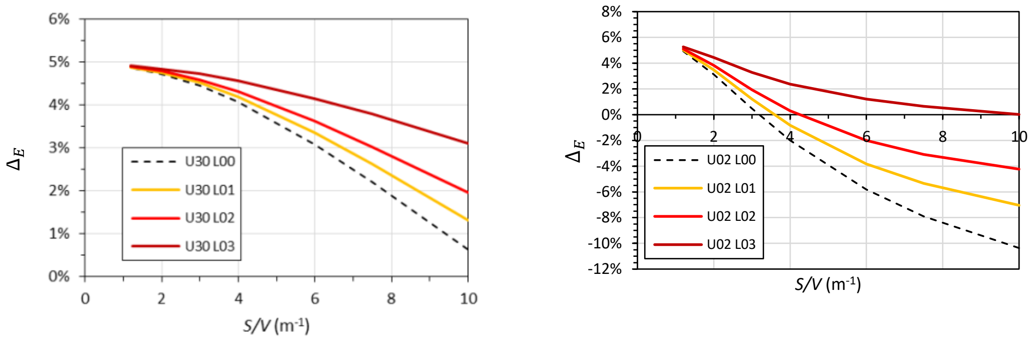
Actually, results of the parametric analysis, on an annual basis, are depicted in figures from 6 to 16, which summarize the outcomes of the performed simulations as a function of the shape factor, *S/V*, namely the ratio of the surface of the tank (i.e. the heat exchange surface to the outdoor environment), *S*, to its volume, *V*. This is an important parameter, which strongly influences the transient behaviour of systems involved in heat transfer processes. Being able to give an account of both the size and thermal response of the water storage, the shape factor was deemed a proper parameter to be used for the parametrical analysis.

Therefore, for all the reported graphs, the shape factor is the X-axis variable. Its values depend on the geometrical dimensions of the tank; the larger the storage is, the smaller the shape factor is.

Specifically, the figures depict the trends of:

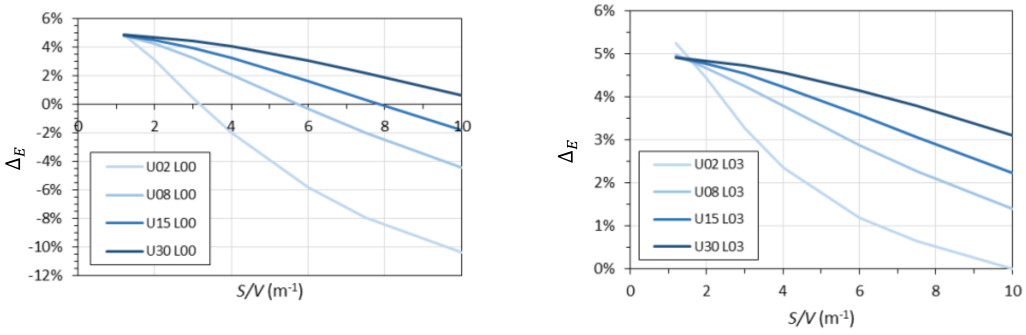
- the increase of the electric energy production due to the use of the PV/T system respect to a standard PV one, Δ_E;
- the ratio of the thermal energy production to the electrical energy production of the standard PV system, R_U;
- the maximum yearly water temperature in the storage tank, $t_{A,max}$;
- the fraction of time during which the water temperature in the storage tank remains higher than 25 °C and 45 °C, respectively, namely f_{25} and f_{45}.

In Fig. 8.6 and Fig. 8.7, the yearly increase of the electric energy production due to the cooling of the PV system is reported.



a) b)

Figure 8.6. Electric energy production increase, Δ_E, for various load conditions: case a) $U = 3.0$ W/m^{2}K; case b) $U = 0.2$ W/m^2/K.



a) b)

Figure 8.7. Electric energy production increase, Δ_E, for various trasmittance values of the storage tank: case a) no thermal load; case b) thermal load condition L03.

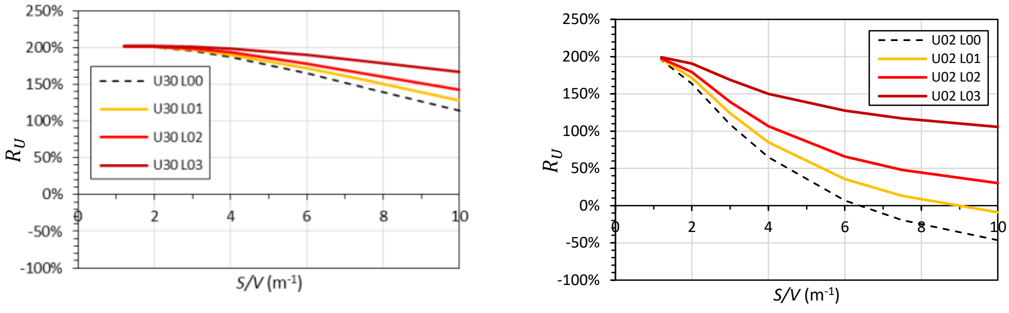
It can be inferred that, the highest increase Δ_E in the energy production always occurs in correspondence of the lowest values of the shape factor (largest storage volume). For S/V <1.8 m^{-1} it was found $4\% < \Delta_E < 5\%$, regardless the values of the involved parameters (load magnitude, tank transmittance).

In addition, Δ_E, whose values never exceed 5%, always decreases when the shape factor increases. The rate and shape of this decreasing trend depend on the thermal load and the thermal transmittance of the tank.

Specifically, regardless the thermal load values, the gradient of the curve rises with S/V, when the less insulated tank is involved (Fig. 8.6-a). On the contrary, the same gradient decreases and tends to 0, when the insulation properties of the tank are improved (Fig. 8.6-b). Moreover, in this latter case (Fig. 8.6-b), when $S/V > 4$ m-^{1}, only the presence of the highest thermal load rate ($L_{H,h} = 62$ W, configuration L03) allowed Δ_E values higher than 0.

The effect of the tank heat loss coefficient is also inferable from Fig. 8.7, where a change in the curve concavity (from upward to downward), occurring when U increases, is also clearly visible for both the depicted load configurations (L00 and L03).

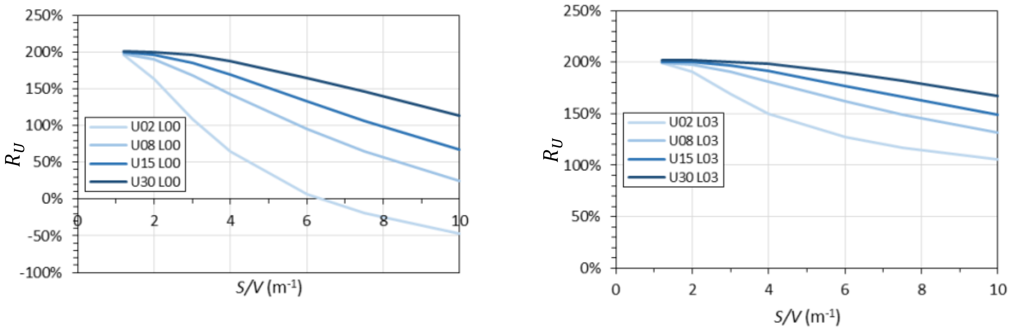
Similar behaviour regards the thermal energy production and it is depicted in Fig. 8.8 and Fig. 8.9, which report the trend of the ratio of the thermal energy production to the electrical energy production of the standard PV system, R_U, versus the shape factor S/V.



a)

b)

Figure 8.8. Ratio of the thermal energy production to the electrical energy production of the standard PV system, R_U: case a) $U = 3.0$ W/m ^{2}K; case b) $U = 0.2$ W/m^2/K.



a)

b)

Figure 8.9. Ratio of the thermal energy production to the electrical energy production of the standard PV system, R_U: case a) no thermal load; case b) thermal load condition L03.

It is worthy of note that when the least insulated tank (Fig. 8.8a, $U = 3.0$ W/m^{2}K) is involved, the improvement of thermal energy production R_U, is almost constant with S/V, for $S/V < 4$ m-^{1}.

On the contrary, for $S/V > 4$ m-^{1} the thermal energy production starts decreasing when S/V rises, for all the considered thermal load configurations.

The decreasing trend, for rising S/V values, always characterizes the results regarding the most insulated tank (Fig. 8.8b, $U = 0.2$ W/m^{2}K). Moreover, in this case, the curve decrease rate is higher than the one obtained in correspondence of large U-values. In other words, the diminution in energy production, for rising S/V values, becomes significant when the transmittance of the storage tank is low.

Presumably, this occurrence is caused by the effect of the warm climate conditions of the site: for the least insulated tank ($U = 3.0$ W/m^{2}K), the outdoor environment contributes to heating the fluid; this contribution counteracts the effect due to the shape factor increase, so that the trend of the yearly available thermal energy versus S/V decreases with a rate lower than the one occurred in correspondence of small U values ($U = 0.2$ W/m^{2}K).

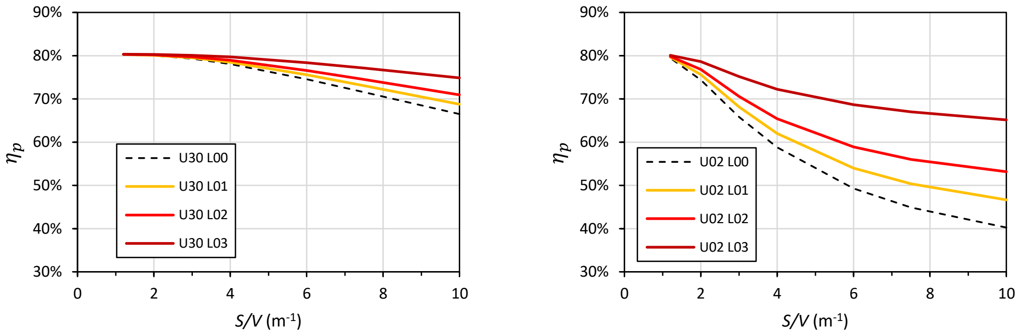
Specifically, when the insulation features of the tank do not allow the external environment to contribute to the heating process of the storage fluid, the amount of produced thermal energy is more strongly influenced by the shape factor S/V.

The influence of the thermal transmittance on the curve concavity is visible in Fig. 8.9. When U increases, the curve concavity changes from upward to downward.

To sum up, Fig. 8.10 reports the trend of primary energy savings efficiency, referred to different load conditions and tank configurations, versus the shape factor S/V. The curves show the same profile as the energy production.

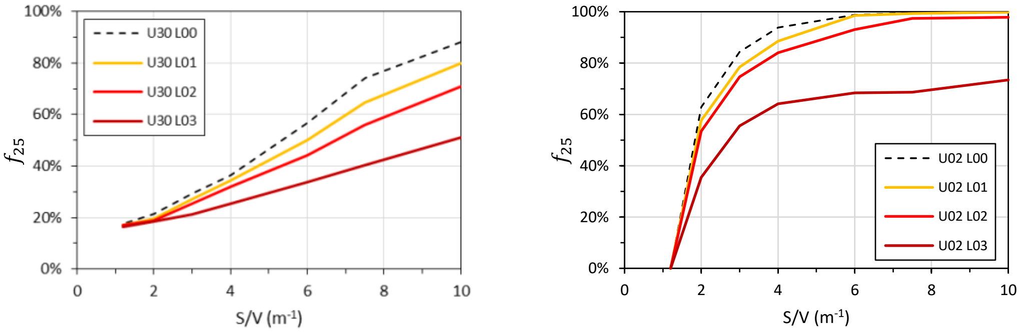
With a view to drawing conclusions about the possible system usability, it is also worth analysing the quality of the generated thermal energy, which can be esteemed as a function of the temperature characterizing the energy production.

From this perspective, information regarding the water storage temperature can be inferred from Figs. 8.10-8.14. They report the year fraction f (f_{25} or f_{45}) during which the water storage temperature keeps higher than a fixed value (either 25 °C or 45 °C) as a function of the shape factor S/V.



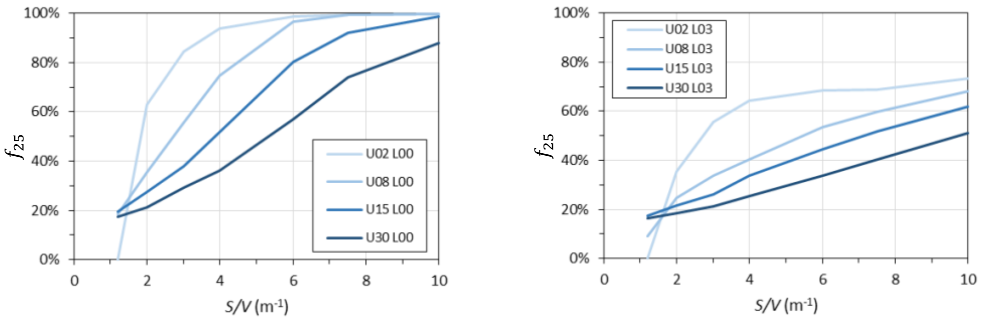
a) b)

Figure 8.10. Annual primary energy savings efficiency: case a) $U = 3.0$ W/m^{2}K; case b) $U = 0.2$ W/m^2/K.



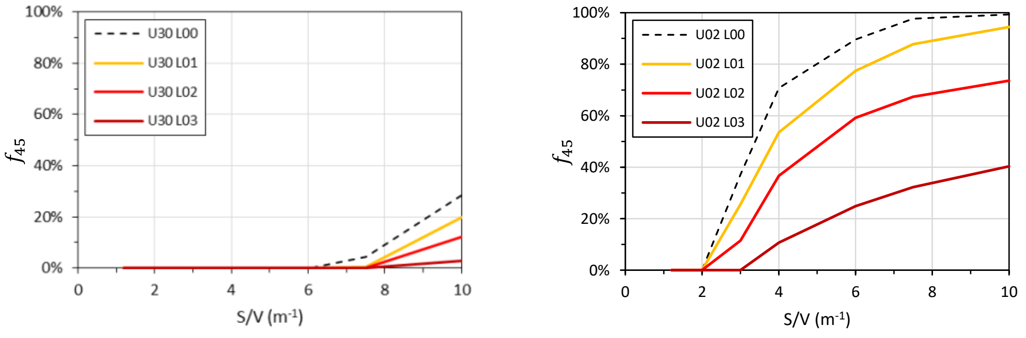
a) b)

Figure 8.11. Fraction of time in a year during which the water temperature remains higher than 25 °C, f_{25}: case a) $U = 3.0$ W/m ^{2}K; case b) $U = 0.2$ W/m^2/K.



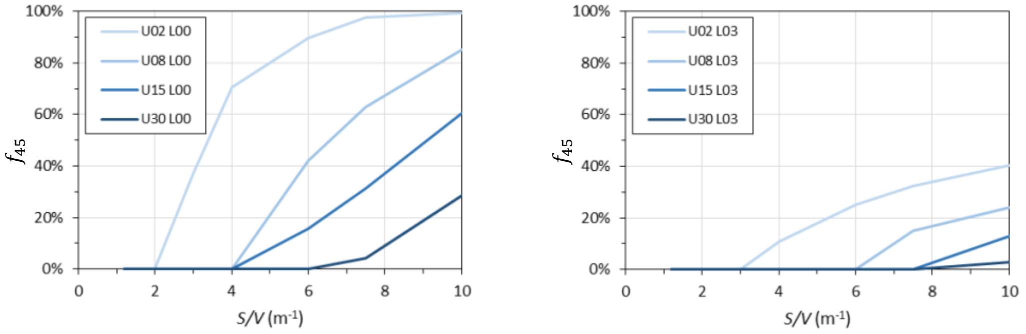
a) b)

Figure 8.12. Fraction of time in a year during which the water temperature remains higher than 25 °C, f_{25}: case a) no thermal load; case b) thermal load condition L03.



a) b)

Figure 8.13. Fraction of time in a year during which the water temperature remains higher than 45 °C, f_{45}: case a) $U = 3.0$ W/m ^{2}K; case b) $U = 0.2$ W/m^2/K.



a) b)

Figure 8.14. Fraction of time in a year during which the water temperature remains higher than 45 °C, f_{45}: case a) no thermal load; case b) thermal load condition L03.

Considering that the groundwater temperature was assumed constant and equal to 15 °C, the water temperature value of 25 °C is considered as representative of those situations where the PV/T systems are only exploited to preheat the thermal fluid. On the contrary, the value of 45 °C usually characterizes thermal energy suitable for satisfying domestic hot water demand.

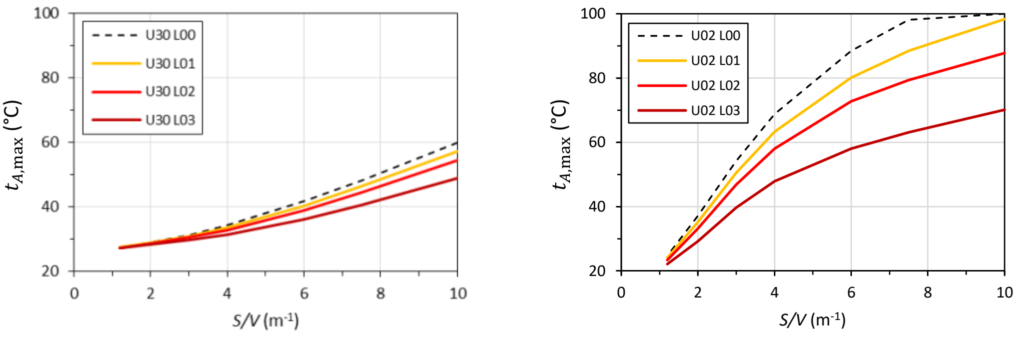
Firstly, it can be noted that both f_{25} and f_{45} increase with S/V. Therefore, albeit the thermal energy production decreases when S/V increases, the quality of the generated energy improves, because higher values of water temperature are maintained for a longer period of time.

For instance, when the most insulated tank is involved (Fig. 8.11b, $U = 0.2$ W/m^{2}K), a water storage with $S/V > 4$ m^{-1} allowed temperatures higher than 25 °C to be kept for a period of time wider than 60% of the whole year, also when the highest value of the load (L03, $L_{H,h} = 62$W) is considered.

On the contrary, with the least insulated tank (Fig. 8.11a, $U = 3.0$ W/m^{2}K) the same result is only yielded for $S/V > 8$ m^{-1} and $L_{H,h} < 31$ W.

This means that, albeit a properly insulated tank may reduce the amount of the generated thermal energy (Fig. 8.8), it contributes to improving the quality of this production, allowing higher values of water temperature to be kept for quite long period of time, also when larger storage volumes are involved.

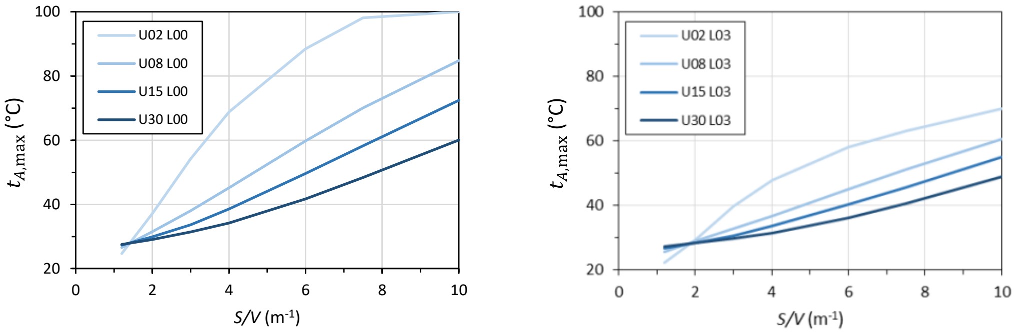
Similar conclusions can be drawn by Fig. 8.15 and Fig. 8.16, which report the trend of the maximumwater storage temperature versus S/V.



a)

b)

Figure 8.15. Maximum yearly temperature in the storage tank, $t_{A,max}$: case a) $U = 3.0$ W/m^{2}K; case b) U = 0.2 W/m^2/K.



a)

b)

Figure 8.16. Maximum yearly temperature in the storage tank, $t_{A,max}$: case a) no thermal load; case b) thermal load condition L03.

8.6 Conclusions

The paper illustrates the results of a parametric analysis, which aims to provide indications about the influence of the combined interaction of the storage structure (size and thermal transmittance) and the thermal load magnitude on the temperature of the working fluid and, therefore, on the performance of PV/T systems.

As a matter of fact, the investigation also regards thermal losses from the storage tank and the possibility of their exploitation to enhance the cooling effect of the PV/T panel, while avoiding remarkable drop of the water storage temperature.

Therefore, the analysis presented is also devoted to the quality of the thermal energy, which is attainable and not only to its global amount.

However, if a water temperature drop is inevitable in order to guarantee acceptable performances from the PV energy conversion point of view, the parametrical analysis reported in the presented article aims to single out the loads that could be better met in any of the examined cases.

These indications can be exploited by designers and researchers to maximize the efficiency of the systems in relation to both electrical and thermal loads and to the features of the water storage.

The system has been analytically modelled considering main components and, in order to simulate its performances, a specific code was elaborated and implemented in a spreadsheet, using VisualBasic™ function and macros.

Several configurations were patterned and simulated, varying the thermal load and both the thermal insulation properties and dimensions of the tank used for thermal storage purposes. Specifically, the electric and thermal energy production and the storage water temperature have been analysed as a function of the shape factor of the storage tank.

Results show that:

- the highest increase of the electricity production Δ_E, with respect to the energy production of the standard PV panel working at the same conditions of the analysed PV/T one, never exceeded 5%, for all the analysed configurations. $\Delta_E < 5\%$.;
- for $S/V < 1.8\ \mathrm{m}^{-1}$ it was found that $4\% < \Delta_E < 5\%$, regardless the values of the involved parameters (load magnitude, tank transmittance);

Therefore, for the sake of electrical production optimization regardless system configurations, storage tanks with small shape factors, $S/V < 1.8\ \mathrm{m}^{-1}$, should be used. This condition makes the cooling effect independent from both the tank insulation features and the thermal load magnitude.

As regards the thermal energy production, the better performances occur for low values of the shape factor and high thermal loads. However, in this case it is very important to consider the temperature of the water in the thermal storage tank, which should reach appropriate values to be used in HVAC plant or for domestic heat water purpose.

The reported results show that small shape factors and poorly insulated tanks do not allow proper values of water temperature to persist for a sufficiently long period of time. The availability of hot water for long periods of time increases with the increase of the shape factor and with the decrease of the thermal transmittance of the tank envelope.

Water storage temperature value, only suitable for preheating purposes, higher of 25 °C for more than 60% of the whole year ($f_{25} > 60\%$) was obtained for:

- $S/V > 2.0$ m^{-1}, regardless the tank insulation properties, when no thermal load is involved;
- $S/V > 8.0$ m^{-1}, regardless the tank insulation properties, when $L_{H,h} = 62$W.

Of course, when meeting the electrical load is the priority, less insulated storage tanks, with smaller shape factors should be preferred, even though it should also be considered that the attainable rise in electrical energy production, with respect to the amount generated by a standard PV panel working at the same condition of the studied PV/T one, never exceeded 5%.

On the contrary, when the main goal is the satisfaction of the thermal demand and a high storage water temperature is needed, tanks with high shape factors and low thermal transmittance are more suited to fulfil the purpose. In this case an adequate design of the storage tank could lead to a remarkable improvement of the system thermal performances, with detrimental effect on the PV electrical production, whose value would tend to the one attainable with a standard PV panel. In this case, the PV/T system could also be configured so that it may act as a cogeneration one, although guaranteeing the same electrical energy production as the standard PV panel working at the same conditions.

In conclusion, PV/T systems have a great potential as cogeneration devices, given that electrical and thermal outputs are generated at the same time.

However, attention should be payed to the system features, so that, at least, the performances of a standard PV system are guaranteed, while assuring that thermal energy at a proper temperature is also generated.

From this perspective, the contribution of the analysis to the topic is based on the fact that the performed parametric study can devise general information regarding the possible ranges of values which may be assumed by the variables/parameters used to describe the operation of the system, in correspondence of various conditions.

This could give practical indications about the possible operational regimes of the system depending on the features of the tank and the magnitude of the load.

For example, when the load magnitude is known, results of the analysis can be used for a rough sizing of the tank, selecting a shape factor able to take into account both the perspectives of electric and thermal energy production.

Therefore, the results of the analysis proposed here may provide useful information, even though additional research is also needed to draw definitive conclusions on this topic, especially when economic considerations are involved or the effects of the climatic conditions are considered. In this direction, the development of the research is being planned.

In addition, a comparison with experimental data will be also the future development of the research activity and, to reach this aim, an experimental apparatus is going to be realized at the Mediterranean university campus.

Chapter 8 Acknowledgment

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Chapter 8 Nomenclature

Δ_E	increase of the electric energy production due to the use of the PV/T system respect to a standard PV one
f_{25}	fraction of time in a year during which the water temperature remains higher than 25°C
f_{45}	fraction of time in a year during which the water temperature remains higher than 45°C
$\dot{G}$	water flow of the fluid in the PV/T system (kg/s).
$\dot{G}_{HW}$	water flow of the fluid in demand loop (kg/s).
I_β	solar irradiance on the panel surface (W/m^2);
$NOCT$	Nominal Operating Cell Temperature (°C);
$\dot{Q}_D^\tau$	thermal flow, which is discarded into the environment through the envelope structure of the water storage (W);
$\dot{Q}_E^\tau$	generated electrical power (W);
$\dot{Q}_T^\tau$	generated thermal power (W);
$\dot{Q}_U^\tau$	global available thermal power, namely the power which is globally at the load disposal (W);
$\dot{Q}_{ue}^\tau$	effective thermal power, namely the thermal power which is actually sent to the thermal load (W);
L_H	yearly thermal load (kWh);

$Q_{E,PV}$	yearly electrical energy, generated by the PV panel characterized by the same features as the studied PV/T one and working at the same conditions (kWh);
$Q_{E,PV/T}$	yearly electrical energy, generated by the PV/T panel (kWh);
Q_U	yearly available thermal energy, at load disposal (kWh);
S_p	area of the panel surface (m^2);
R_U	ratio of the thermal energy production to the electrical energy production of the standard PV system (non-dimens.);
R_E	ratio of the electrical energy production due to the use of the PV/T system respect to a standard PV one (non-dimens.);
t_a	air temperature (°C);
$t_{F,A}$	storage temperature (°C);
$t_{F,basin}$	groundwater temperature (°C);
$t_{c,PV}$	cell temperature of a standard PV system operating at the same condition of the actual PV/T plant (°C);
$t_{c,PV/T}$	actual cell temperature of the PV/T collector (°C);
$t_{F,A}$	water temperature in the storage system (°C);
$t_{F,iA}$	inlet water temperature to the storage system (°C);
$t_{F,oA}$	outlet water temperature of the water storage (°C);
$t_{F,iC}$	inlet water temperature to the collector (°C);
$t_{F,oC}$	outlet water temperature from the collector (°C);
t_p	temperature of the absorber plate (°C);
Δ_E	increase of the electric energy production due to the use of the PV/T system respect to a standard PV one;
η_p	primary energy saving efficiency (non-dimens.);
η_e	electrical power generation efficiency of the Italian energy system (non-dimens.);
η_r	nominal efficiency of the PV panel (non-dimens.);
β	temperature coefficient of the panel (%°C^{-1});
η_{PV}	electrical efficiency (non-dimens.);
η_0, k_1, k_2	parameters characterizing the thermal collector (non-dimens.);
η_T	thermal efficiency (non-dimens.).

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SECTION I.C – Results and Findings

The study presented in this section, aimed at assessing the effect of the thermal storage dimensions on the performances of a solar photovoltaic-thermal – PV/T system by means of a parametric analysis, led to the following observations:

- for the sake of electrical production optimization, storage tanks with small shape factors ($S/V < 1.8 \text{ m}^{-1}$) should be used; this condition makes the cooling effect independent from both the tank insulation features and the thermal load magnitude;
- as regards the thermal energy production, the better performances occur for low values of the shape factor and high thermal loads;
- small shape factors and poorly insulated tanks do not allow proper values of water temperature to persist for a sufficiently long period of time;
- the availability of hot water for long periods of time increases with the increase of the shape factor and with the decrease of the thermal transmittance ofthe tank envelope;
- water storage temperature values are only suitable for preheating purposes ($T > 25°C$ for more than 60% of a whole year).

PART I – Interventions on Single Buildings

SECTION I.D – Sites' Climate Influence

A strong attention to the performance of the building envelope has been paid by the European Union, hence by the research community, in recent years. In light of this it has emerged the need of reliable tools to obtain a synthetic quantitative judgement about the effectiveness of the selected interventions considering the climatic context in which they are implemented, in order to compare them from both the energy and the indoor comfort points of view. On purpose, this section discusses the use of some new suitably implemented climatic indicators and parameters.
This section of the dissertation consists of two chapters:

Chapter 9 - Considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions

Chapter 10 - Comparing indoor performances of a building equipped with four different roof configurations in 65 Italian sites

Chapter 9 - Considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions

This chapter consists in the following conference paper:
Cirrincione, L., La Gennusa, M., Peri, G., Rizzo, G., Scaccianoce, G., Considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions, (2020) Proceedings - 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020, art. no. 9160783.
DOI: https://doi.org/10.1109/eeeic/icpseurope49358.2020.9160783

Abstract: Green roofs are building components that have become increasingly common in urban contexts because other than the general improvement of the aesthetics of the buildings equipped with them, they have demonstrated to positively improve the building energy performance. Consequently, it would be useful for technicians to have easy and reliable indicators to achieve a synthetic quantitative judgement about the effectiveness of green roofs by an energy perspective compared to others building envelope technologies, for different climates. In sight of the definition of such an indicator, or at least of its properties, some considerations aimed at this purpose, especially concerning the use of new climatic indicators instead of the commonly used ones (i.e. heating and cooling degree days), are presented here.

Keywords: building energy efficiency, green roof; cool roof, climatic vector, Degree Days; Leaf Area Index.

9.1 Introduction

As it is well known, the energy saving and the improvement of the energy efficiency of the building sector is a topic particularly investigated by the European Union, with a strong attention to the performance of the building envelope [1; 2; 3].

Among the innovative components of the building envelope, for instance, green roofs are increasingly used in our cities because, other than the general improvement of the aesthetics of the buildings equipped with them, they have demonstrated to positively improve the building energy performance.

There exist in fact several research studies addressing their impact on energy consumption of buildings, both on an annual and seasonal basis. Based on a literature review, it has arisen, indeed, that on one hand there is a wide agreement among researchers on the positive contribution provided by these components during summer roofs to the building equipped with them [4; 5; 6], while, on the other hand, the performance of vegetated roofs in winter is somehow a debated issue since green roofs mostly reduce the total heating load [7] but in some cases their contribution is almost insignificant or even to some extent adverse [8; 9]. Nonetheless, vegetated roofs have mostly a positive impact on the total annual energy consumption of buildings because they imply a reduction of the annual energy demand for air conditioning of the building compared to a traditional roof [10]. Vegetated roofs have also been demonstrated to improve the indoor comfort levels of buildings [11].

Another envelope component that has become quite popular in urban contexts is represented by the high-albedo roof, also called "*cool"* roof. Unlike green roofs, such type of roofing technology shows a well-defined behaviour: positively impacts in summer proving some energy savings for cooling, whereas it causes a negative impact in winter as it increases the heating energy demand [12; 13; 14; 15].

In this framework, it would be useful for technicians to have easy and reliable tools to achieve a synthetic quantitative judgement about the effectiveness of green roofs or cool roofs by an energy perspective compared to others building envelope technologies, for different climates.

To the best of our knowledge, such an indicator for green roofs does not seem to exist in literature, instead.

To date, there is available in literature an indicator that provides a synthetic quantitative judgement about the applicability of cool roofs by an energy point of view. In detail, the indicator here mentioned is that proposed by two American researchers, namely Levinson and Akbari [16], which combines the positive impact provided in summer by cool roofs (energy savings for cooling) with the negative impact provided in winter (increases of the heating energy demand), indicated as *l(x,y)*, expressed as follows:

$$l(x,y) = \frac{\eta_h^{-1} \times g(x,y)}{e(x,y) \times EER \times 0{,}01\ therm/kBTU} \tag{9.1}$$

where η_h is the dimensionless efficiency of the heating system, *g(x,y)* is the increase of the annual heating energy (gas) use per CRA (the "Conditioned Roof Area") [therm/area], *e(x,y)* is the decrease of the annual cooling energy (electricity) use per

CRA [kWh/area], and EER (Energy Efficiency Ratio) is the dimensional coefficient of performance of the cooling equipment [BTU/(hW)].
Therefore, in sight of the definition of an indicator, or at least of its properties, capable to assess synthetically the effectiveness of green roofs, at different climatic conditions, some considerations aimed at this purpose are presented in this paper.
Specifically, after briefly reporting on the opportunity to extend the use of Levinson and Akbari's indicator also to green roofs, we analyse some newly introduced climatic indicators in order of estimating their feasibility/reliability in the case of innovative building components especially green roofs to be incorporated into such new indicator. Particularly, we consider the climatic vector Vc, recently introduced [17], and we compare its performance with that of the classical climatic indicators heating and cooling degree days (HDD and CDD). Therefore, we compare its performance for buildings located in different Italian sites (characterized by different climatic zones), assessing results for summer and winter season (considered separable) and in the case of traditional roofs and vegetated roofs.
In addition, a discussion on the incidence of the time variability of vegetation-related parameters, especially of Leaf Area Index (LAI), into energy consumption estimation of buildings is presented, along with some surprising findings.
In the following, a brief description of both the climatic vector Vc and the index of climatic severity, *C* by means of which such climatic indicator V_c, was firstly introduced is provided.

9.2 Index of Climatic Severity

As it is well known, the Italian territory has been subdivided, on the basis of a climatic index, namely heating degree-day (HDD), in suitable winter climatic zones. The increasingly presence of summer air conditioning systems in buildings, with the consequent increase of the energy consumptions, implies the necessity to determine limit values also of the energy needs for the summer air conditioning. On purpose, some researchers of an Italian public research institute, *i.e.* the national agency for the new technologies, energy, and the sustainable economic development (ENEA) have proposed a summer index of climatic severity, *C*, for the definition of summer climatic zones, that assesses the cooling energy need, normalized with respect to the characteristics of the building. The suggested expression embeds also the winter case, thus allowing a uniform classification [10] through the whole year. In more detail, the index of climatic severity, *C*, is defined as follows:

$$C = |\vec{V}_C| - |\vec{V}_{C,ref}| \tag{9.2}$$

where:

- $\vec{V}_C$ is a climatic vector of a given site;
- $\vec{V}_{C,ref}$ is a reference climatic vector.

More specifically, these two vectors are defined as follows:

$$\vec{V}_C = \dot{\Theta}_e\vec{\imath} + \dot{\mathrm{X}}_e\vec{\jmath} + \dot{\Upsilon}_e\vec{k} \tag{9.3}$$

$$\vec{V}_{C,ref} = \dot{\Theta}_i\vec{\imath} + \dot{\mathrm{X}}_i\vec{\jmath} + \dot{\Upsilon}_i\vec{k} \tag{9.4}$$

The vectors' components are representative of the outdoor and indoor climatic conditions, respectively. In detail, they are given by the ratio between the climatic variables cumulated for the site in the period, *T,* and the period, *T*, itself, each of them normalized with respect to the average value of the components themselves in the n sites of the climatic sample assumed in the national territory. For example, considering the vector component related to outdoor air temperature, $\dot{\Theta}_e$, it is defined as follows:

$$\dot{\Theta}_e = \frac{\frac{1}{T}\int_T \vartheta_e dt}{\frac{1}{n}\sum_n \frac{1}{T}\int_T \vartheta_e\, dt} = \frac{\Theta_e}{\Theta_*} \tag{9.5}$$

Similar equations are used for other climatic variables. The energy, *E*, needed to maintain the set point of the indoor conditions of the volume (*V*) of the building during a fixed period (*T*) can thus be calculated using the following formula:

$$\frac{E}{VT} = A\Theta_e + B\mathrm{X}_e + C\Upsilon_e - \left[A\Theta_i + B\mathrm{X}_i + C\Upsilon_i\right] \tag{9.6}$$

It can also be expressed in a more compact way, as follows:

$$\frac{E}{VT} = \vec{V}_B\vec{V}_C - \vec{V'}_B\vec{V}_{C,ref} \tag{9.7}$$

where $\vec{V}_B$ is a characteristic vector related to the building with components A, B, and C. The index of climatic severity, C, defines:

$$C = \frac{E}{V \cdot T \cdot |V_B| \cos{(\omega)}} \approx |\vec{V}_C| - |\vec{V}_{C,ref}| \tag{9.8}$$

Anyway, the (6.2) states that the index of climatic severity *C* is a linear function of magnitude of climatic vector, considering that the magnitude of reference climatic vector is constant. Hence, in the following the authors have taken into account directly the magnitude of climatic vector for the analysis and comparisons.

9.3 The Methodological Approach

9.3.A Is the Levinson and Akbari indicator for cool roofs suitable also for green roofs?

With the aim of singling out an indicator aimed at describing the energy efficiency of buildings with green roofs at different climatic conditions, firstly we decided to examine whether the Levinson and Akbari's indicator might have been extended also to green roofs, despite their somehow contrasting behaviours.

Although the indicator proposed for cool roofs seems quite an appealing solution for the purpose here stated, since it provides a synthetic quantitative judgement about the applicability of cool roof by an energy point of view, first results of our analysis, already shown in [10], have indicated that this indicator does not seem to be applicable as it is also to green roofs, but for green roofs characterized by low LAI values (LAI = 1 was assumed in that analysis) with the due differences. In this case, in fact, - based on the energy simulations, conducted using EnergyPlus code, of a reference building for the Italian medium size office edifices, covering 65 sites in Italy, from North to South (characterized by HDD ranging approximately between 1000 and 3000 and CDD ranging between 0 and 120) - it was found that green roof with LAI values equal to one reduces the heating energy need compared to the standard roof in winter, while it increases the cooling energy demand compared to that of standard roof in summer. In other words, green roofs with low LAI were found to show an opposite behaviour with respect to cool roofs. On the contrary, in the case of green roofs with high values of LAI (LAI = 5 was assumed in the analysis), green roof options were found to reduce (but for few exceptions) both the heating and cooling energy need, when compared to the standard roof.

As that, the indicator only signals the relative benefits of heating to cooling reductions, and thus it does not seem to be applicable as it is, unless a benchmark value of energy convenience is set.

In Table 9.1 the main outcomes of this first analysis [10] are summarized.

Table 9.1. Overview of the main findings of an authors' previous study on the applicability of the Levinson and Akbari'a indicator for cool roofs also to green roofs (G.R. = Green Roofs; C.R. = Cool Roofs; HDD = Heating Degree Days; CDD = Cooling Degree Days).

	Winter	**Summer**			
Roof configuration	***Energy needs for heating compared to a traditional roof***	***Energy needs for cooling compared to a traditional roof***	**I(x,y) <1**	**Dependence on HDD and CCD**	**Italian sites applications**
Green Roof low LAI	Reduced	Increased	Increases of cooling need are higher than reduction of heating need	Unfavourable for: low HDD and high CDD Favourable for: high HDD and low CDD	Most favourable in northern Italy
Green Roof high LAI	Reduced	Reduced	Reduction of energy demand for cooling is higher than the reduction of the energy demand for heating	Unfavourable for: high HDD and low CDD Favourable for: low HDD and high CDD	Most favourable in southern Italy
Cool Roof	Increased	Reduced	Increases of energy demand for heating are smaller than decreases of energy demand for cooling	Unfavourable for: low HDD and low CDD Favourable for: high HDD and high CDD	Mostly favourable in southern and coastal areas of Italy

9.3.B On the involvement of new climatic indeces into the indicator for green roofs

Results shown particularly in penultimate column of Table 9.1 (named "Dependence on HDD and CCD"), indicating the obtained dependence between the effectiveness/convenience of adopting a green roof and the degree days of the site where it is implemented, suggested us to restart and analyse some further climatic indicators in order of estimating their feasibility/reliability in the case of innovative building components.

In more detail, the approach - that we followed subsequently - essentially consisted in two assessments. A first assessment was performed by considering a sample of 61 cities located in Italy.

Firstly, the heating and cooling start and end dates for evaluating Heating and Cooling Degree Days as well as the magnitudes of climatic vectors for heating and cooling seasons for each site have been considered, specifically those suggested by the UNI 10349-3 Italian Standard [18], namely April, 15 and October, 14. Afterwards, on the basis of the days previously fixed, we calculated both the magnitude of climatic vector, V_C in summer and winter, and the heating degree days

(HDD) and cooling degree days (CDD) for each of the 61 sites. Finally, a pair-wise comparison among these four parameters, was made.

A second assessment was conducted by performing, for 21 different sites of the previously cited 61, energy simulations of a standard module, namely Case 600 of best-test ANSI/ASHRAE Standard 140 (Fig. 9.1), with and without the green roof.

These 21 sites have been chosen as representative of all 61 sites, by subdividing the variation range of Vc values in four parts and choosing the site closer to centre value for each of four ranges; this procedure has been repeated for the Vc values calculated for heating and cooling seasons. This procedure has also been applied both considering equal sizes of four ranges and subdividing the variation range in quartiles.

Specifically, we have selected a given green roof (with a given LAI and plant height); afterwards, we have calculated the $Q_{Heating}$ and $Q_{cooling}$ for the module equipped with the selected green roof. Such calculation was made also for the standard configuration. Finally, we have compared the variation of the energy consumption against the HDD with that against winter V_C with and without the green roof, and we compared the variation of the energy consumption against the CDD with that against the summer V_C with and without the green roof.

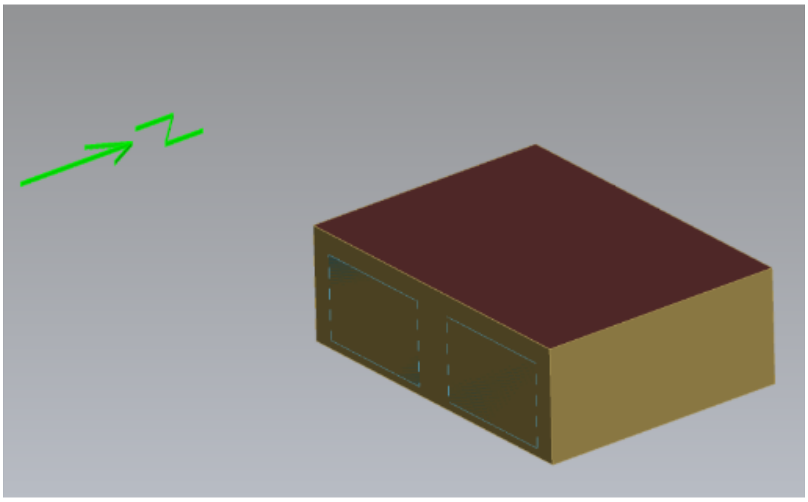

Figure 9.1. Sketch of the module used for simulation in energyplus software.

The weather data used in this study have been taken from the EnergyPlus climate database. Among the climatic data, those referred to precipitation rates were not used in the analysis. The sites considered in this study have been chosen on the base of the climatic data available in the EnergyPlus software for the Italian territory. During this process, sites with unusual or extreme climatic data have been excluded, therefore 61 sites have been taken into account.

9.4 Results

In this paragraph results of both above-cited assessments (*section* 9.3.B) are shown. As mentioned earlier, the magnitude of climatic vector V_C and degree days have been calculated both for heating season and for cooling ones for each of the 61 sites. To capture the differences among these two indicators, Figure 9.2 reports a diagram containing a straight line with normalized values of the two indicators for each of the 61 sites.

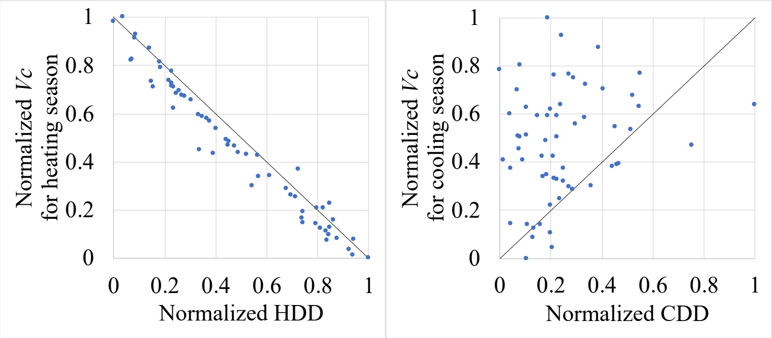

Figure 9.2. Comparison diagrams with straight lines as perfect relationship of normalized values of considerated climatic indicators.

Figure 9.2 diagrams highlight the existence of a correlation between V_C and Degree Days during the heating season, while no correlation between V_C and Degree Days in the cooling season seems to occur.

As regards the second assessment on the 21 sites, the obtained values on the energy consumptions for heating and cooling of the building module equipped with either a standard roof and a green roof characterized by a LAI value equal to 5, have been plotted versus both Degree Days and V_C, for heating and cooling seasons (Figure 9.3-9.6).

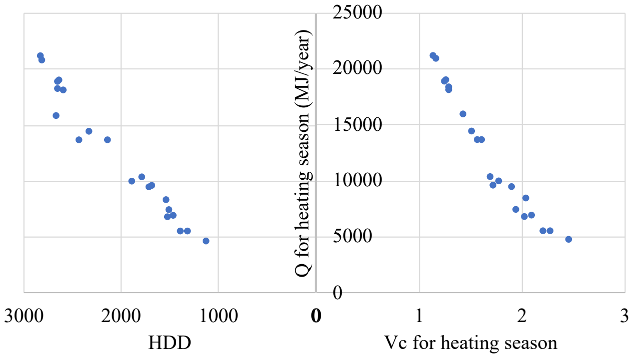

Figure 9.3. Annual energy consumption for climatization in heating season of the building module equipped with **standard roof** respect to HDD (left side) and V_C (right side).

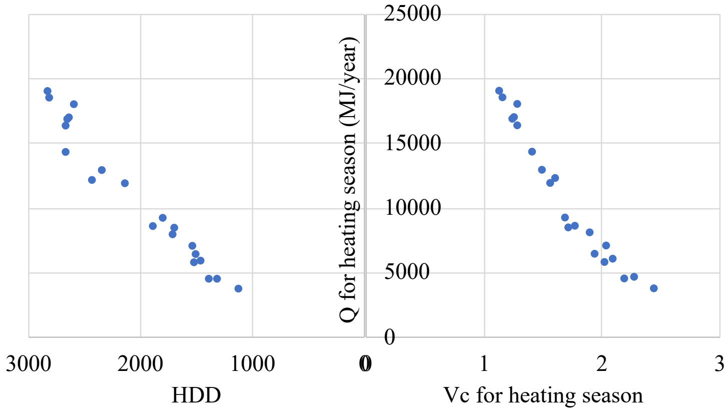

Figure 9.4. Annual energy consumption for climatization in heating season of the building module equipped with **green roof** having LAI equal to 5 against HDD (left side) and *V*C (right side).

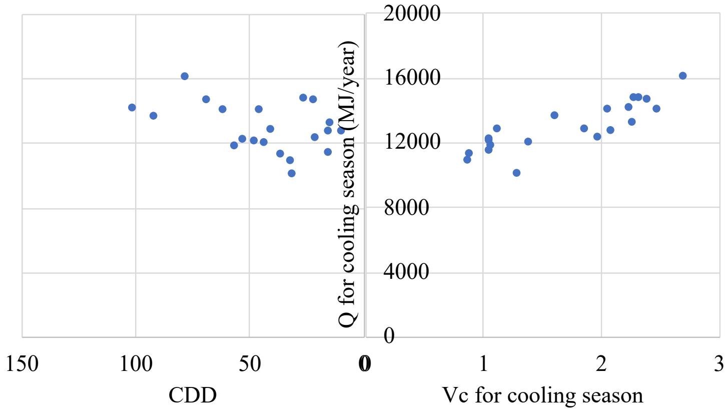

Figure 9.5. Annual energy consumption for climatization in cooling season of the building module equipped with **standard roof** against HDD (left side) and *V*C (right side).

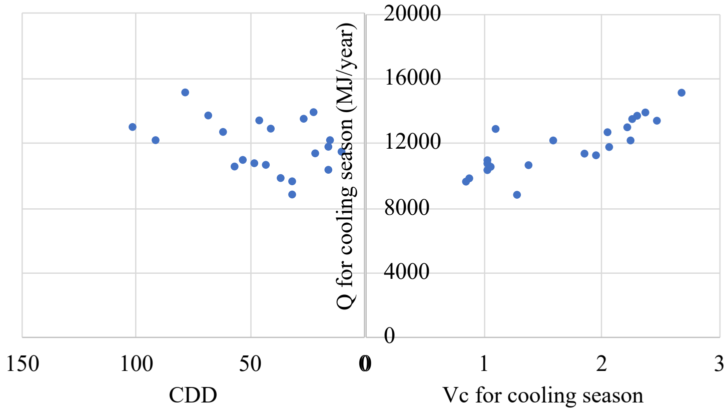

Figure 9.6. Annual energy consumption for climatization in cooling season of the building module equipped with **green roof** having LAI equal to 5 against CDD (left side) and *V*C (right side).

The diagrams referred to a standard roof (Figures 9.3 and 9.5) and those referred to a green roof (Figures 9.4 and 9.6) show an opposite behaviour of the climatic vector V_C compared to the HDD (as yet shown by left side diagram of Figure 9.3), while a similar behaviour between climatic vector V_C and the CDD has been observed. In other words, the greater the HDD is, the greater the $Q_{Heating}$ is, but an opposite behaviour has been found in case of V_C. As regards the cooling energy loads, it a similar behaviour of V_C and CDD has been found, that is: the greater the CDD or V_C is the greater the $Q_{cooling}$ is.

When comparing the dependence of “green roofs with high LAI” on HDD (see Table 9.1) with that on V_C (winter), it arises that green roofs result to be favorable with low HDD and high V_C. While, when comparing the dependence of “green roofs with high LAI” on CDD (see Table 9.1) with that on V_C (summer), it arises that green roofs result to be favorable with high CCD and low V_C.

9.5 Discussion

Other than assessing the reliability/feasibility of the climatic vector V_C to possibly incorporate it into a new indicator for assessing the energy efficiency of buildings with green roofs, we have studied also the incidence of the time variability of vegetation-related parameters on the energy consumption estimation of buildings equipped with such kind of components. More specifically, we decided to consider LAI as a vegetation related parameter, as it reflects the different growth stages of plant species used in a green roof and also because it has been proved to significantly influence the building energy balance, especially in summer [5].

It seems worth noting that the surface albedo of cool roofs is a constant parameter over the year, while in the case of green roofs, during the year a certain LAI variability might be found according to the different growth phases of the plants. In more detail, (overlooking the transient phase subsequent to the implantation) in certain periods of the year (presumably in winter) low LAI values would likely be registered, while in others (presumably in summer) higher LAI values would be observed. Provided that, as shown in Figure 9.7, heating energy consumption reasonably increases when LAI increases (because of the higher shading effect and evapotranspiration), while cooling energy need decreases when LAI increases (because of the higher shading effect and evapotranspiration), different conditions can be found: there are cases in which the green roof delivers a benefit in both winter and summer and cases in which it provides a benefit only in winter, or only in summer.

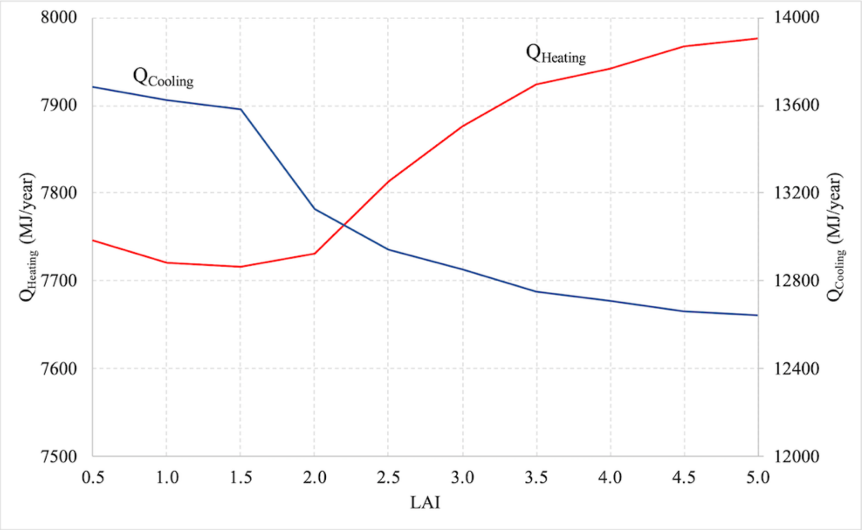

Figure 9.7. Energy load behaviours for heating and cooling as LAI changes (for the town of Naples).

Consequently, if for buildings equipped with a cool roof an indicator such as that proposed by Levinson and Akbari is suitable, for buildings equipped with green roofs, which have, instead, dynamic characteristics it would likely be more appropriate to use an indicator that takes into consideration the time variability of vegetation-related parameters such as, for instance, LAI.

Hence, after having assumed a certain height of plant and a hypothetical monthly variation of LAI over a year (Figure 9.8) - clearly such variation may change depending on the vegetable species considered -, we have calculated and thus plotted the monthly variation of the energy consumption of the above cited standard module, namely Case 600 of best-test ANSI/ASHRAE Standard 140, with and without the green roof, *i.e.* $Q_{Heating + Cooling}$ (month) for four sites, among the previously cited 61.

These four sites can be considered as representative of the climatic conditions typically occurring in the whole Italian territory. They have been selected using the climatic vector V_C, previously calculated for the 61 sites, for the cooling season as a reference parameter.

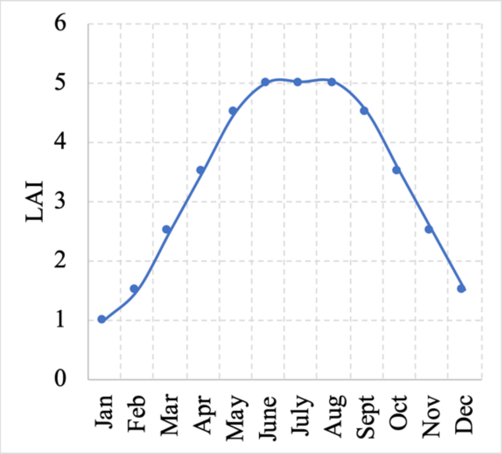

Figure 9.8. Hypothetical monthly variation of LAI over a year assumed in the analysis here presented.

Results of the analysis are illustrated in Table 9.2, which highlights for each considered site the different energy consumption with and without the green roof, considering a monthly variable LAI or a fixed LAI value (almost always equal to 5). Site 1 is located in the North of Italy, instead Site 4 is located in South of Italy.

Table 9.2. Annual energy consumption for climatization for different configuration of roof.

Site	Annual energy consumption for climatization (toe)				
	Standard roof	***Green roof with fixed value of LAI***	***Green roof with variable value of LAI***	***Red. (%)***	***Red. (%)***
Site 1	0.78556	0.7035	0.7022	10.5	10.6
Site 2	0.74579	0.6676	0.6665	10.5	10.6
Site 3	0.52758	0.4725	0.4708	10.4	10.8
Site 4	0.48838	0.4452	0.4456	8.8	8.8

Data reported in Table 9.2 signal, on the one hand, the positive contribution provided by the presence of the green roof, and on the other hand – and more importantly - that the variability of LAI over the year does not seem to play a significant role when estimating the energy consumption of a building equipped with such kind of component. In other words, almost similar results have been found when using either a fixed constant LAI value or a time-dependent LAI. This is a quite a unexpected result, which should be taken into consideration in the development process of an indicator for green roofs.

9.6 Conclusion

Green roofs are building components that have become more and more common in urban contexts. Consequently, it would be useful for technicians to have at their disposal easy and reliable tools by means of which achieving a synthetic quantitative judgement about the effectiveness of green roofs by an energy point of view with respect to others building envelope technologies, for different climatic conditions.

In sight of the definition of an indicator, or at least of its general properties, capable to assess synthetically the effectiveness of innovative building components, like green roofs, at different climatic conditions, some considerations aimed at this purpose have been presented in this paper. Specifically, they concern the use of new climatic indicators instead of the commonly used ones (HDD and CDD), in the case of innovative building components, and the opportunity to consider the time variability of vegetation-related parameters for the energy consumption estimation of buildings equipped with these components.

Anyway, further analyses are certainly needed and the way is still long. Nevertheless, findings of the present work represent a starting point and might provide a contribution for the development process of such new indicator.

Chapter 9 Acknowledgment

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Chapter 9 References

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Chapter 10 - Comparing indoor performances of a building equipped with four different roof configurations in 65 Italian sites

This chapter consists in the following conference paper:
Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., Comparing indoor performances of a building equipped with four different roof configurations in 65 Italian sites, (2020) 20th IEEE Mediterranean Electrotechnical Conference, MELECON 2020 - Proceedings, art. no. 9140533, pp. 488-493.
DOI: https://doi.org/10.1109/melecon48756.2020.9140533

Abstract: Despite the increasing concern of institutions and technical organizations toward the improvement of the building energy (and, therefore, environmental) efficiency, the main goal of technicians should be also devoted toward the levels of internal thermal comfort that buildings are able to realize. As that, the relationships between energy performances and comfort conditions provided by the enclosures are of paramount importance in guiding designers in their work. In this paper, the influence of diverse roof construction typologies on energy and indoor performance of buildings has been investigated, in different Italian sites during heating and cooling seasons. In addition, it must be properly considered that buildings operate in given climate and weather contexts that deeply affect their performances. Hence, for taking into account the different weather conditions of each site, a new parameter has been used, that is the “Climatic Severity Index” corresponding to a value of magnitude of a climatic vector less a constant value, recently released by an Italian technical standard. The actions for improving the energy efficiency sometimes lead to a reduction of indoor comfort, therefore, not always easily applicable.

Keywords: Green roof, Cool roof, Thermal comfort, Climatic Severity Index.

10.1 Introduction

In the last decades, worldwide countries’ policies have been keeping a high level of attention on energy conservation in the building sector, especially the Developed Countries, in order to reduce climate change, other relevant environmental impacts and to enhance the security of energy supply and the economic features linked to them [1-5]. Moreover, it is expected that the well-known weigh of 40% of buildings’ stock on the energy consumption in developed countries will go through a further acceleration over the next decade [6]. Furthermore, the major energy demand within a building is due to its Heating Ventilation and Air-Conditioning (HVAC) system (accounting for 40–60% of the whole energy consumption) [6,7].

In this context, the necessity to reduce the buildings' thermal loads in order to reduce the design size and energy demand of HVAC systems should be therefore the main purpose of the energy policies related to the building sector. Consequently, the necessity to improve the envelope of the building is a fundamental issue, since its characteristics and configurations strongly affect the building energy behavior [8]. In fact, if properly designed, envelopes can contribute to minimize the overall energy demand of the buildings, thus allowing the achievement of a high-energy performance, which is the basis of the recently introduced nearly Zero Energy Building (nZEB) concept [9,10].

Among the new building components, green roofs are being used widely in urban contexts nowadays because, apart from the generally aesthetical benefits provided to buildings equipped with them, they have proved to deliver a positive contribution to the thermal behaviour of buildings [11,12]. Indeed, their effects on the energy consumption of the building have been largely investigated in recent years. Many studies indicate significant reductions of the annual building energy use obtainable by means of this kind of components, especially in the case of their installation on existing roofs characterized by a low level of insulation [13]. In the same way, cool roof components represent another technology able to reduce the rising temperature of roofs. This technology uses a coating with high values of reflectance throughout all the spectrum, in particular in its infrared part. The albedo of cool coating is generally comprised between 0.65 and 0.85. This technology has been investigated for two main reasons: improving building energy performance and indoor comfort conditions, and reducing the urban heat island (UHI) effect and outdoor discomfort [14-16].

10.2 Indoor environment and energy performance of building

Usually people are exposed to moderate thermal environment, in which it is possible achieving a thermohygrometric wellness state. In order to assess the thermohygrometric conditions in these environments, the PMV (predicted mean vote) index and the correlated PPD (predicted percentage of dissatisfied) are utilized [17,18]. In particular, the PMV index is a function of six parameters, two of these take into account the subjective conditions of people (metabolism and thermal resistance of clothing) while the other four parameters take into account the indoor microclimate conditions (air temperature, relative humidity and relative velocity, and mean radiative temperature). The PPD is a function of PMV index and exactly the equation is:

$$\mathrm{PPD} = 100 - 95 \exp(-0.03353\ \mathrm{PMV}^4 - 0.2179\ \mathrm{PMV}^2) \qquad (10.1)$$

The neutrality of the people thermal sensation is given by a PMV value equal to zero, i.e. such value corresponds to optimal thermal comfort conditions; while, a positive value marks a sensation of warmth, instead a negative value signals a sensation of cold. However, to a PMV equal to zero it is associated a PPD value of 5%, meaning that the case for which all people simultaneously feel a thermal sensation of neutrality never happens [19,20]. In this work, in order to assess the indoor comfort levels, the average values of PMV and the frequency with which the hourly PPD exceeded a 10% value for each site and for each roof option have been evaluated.

On the other hand, the Energy Performance index (EP) [21,22] has been used in order to evaluate the energy behaviour of building at different latitudes. Specifically, the authors have indicated with EP_H and EP_C the ratio of primary energy demand to volume of the considered building for heating season and for cooling season, respectively.

10.3 Simulation

In the following, after a brief description of the reference building and the weather climatic conditions, considered for the analysis, the results of the simulation have been reported, in order to highlight the behaviour of the PMV indicator and the Energy Performance (EP) index related to the climate of 65 Italian sites.

Moreover, some considerations on the heat-related mortality due to a heatwave occurrence have been briefly debated.

10.3.A The analysed office building, green roofs and cool roof

In order of comparing the behaviour of building in different climate sites, a reference building has been chosen. In particular, in this work, a reference building for Italian medium size office edifices has been used as a model for the analyses [23]. The building has a covered area of 2400 m^2 and consists of five storeys above the ground of 480 m^2 each. For the aim of this work, only the top level of this building has been analysed, assuming its floor as adiabatic (see Fig. 10.1).

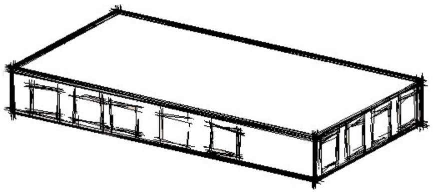

Figure 10.1. Sketch of the analysed reference building's floor.

Table 10.1. Thermo-physical properties of the opaque components of the envelope.

Component type	Thickness (m)	Thermal Transmittance ($W/m^2 °C$)	Internal heat capacity ($kJ/m^2 °C$)
Wall	0.37	0.773	614
Flat roof	0.30	0.851	359

Focusing the analysis only on the top floor allows to better highlight the effect of the type of roof on the energy and indoor performance of the building. The effect of the roof, in fact, mainly affects the energy demand and the indoor comfort levels of the top floor, while, the lower floors are hardly affected.

Table 10.1 reports the thermo-physical properties of the opaque envelope elements of the structure (external walls and roof), while to the glazed surfaces have been assigned a glass thermal transmittance and a Solar Heat Gain Coefficient of 3.146 W/m^2K and 0.713, respectively.

With regard to the use of this floor, the various parameters set for simulation are reported in Table 10.2, such as people occupancy, lighting load, electric equipment load, ventilation, and infiltration, as well as the heating and cooling set points, along with pertinent schedules. The value reported in Table 10.2 were based on the studies treated in [24] and [25].

A gas boiler and an air-cooled chiller are the primary feeding systems for the internal pipe fan coil units, which allow both heating and cooling needs to be met [24]. Hence, two different energy carriers feed the cooling and heating primary systems: electricity and natural gas, respectively.

The global energy consumption of the selected building was evaluated in terms of primary energy, using suitable conversion factors for natural gas and for electricity, which in the present analysis assume the values of 1 and 2.174, respectively [22, 26].

In this work the indoor comfort levels and the energy performances of three types of roof have been modelled and analysed, namely: a cool roof (with a solar absorptance of 0.2), a green roof with a plant height of 5 cm and low leaf area index (namely LAI = 1), and a green roof with a plant height of 20 cm and high LAI (namely LAI = 5).

In running the simulation code, regarding the irrigation of the green roof, a smart modality has been selected, with an irrigation level of 0.002 meters of water per hour from October 1st until May 31th, and 0.004 meters of water per hour for the rest of the year.

The values of the main parameters needed to simulate the green roof using the EnergyPlus simulation code are listed in Table 10.3 [27].

Table 10.2. Parameters set utilized for running the simulations.

	Values adopted for simulations	
	Weekday 9-17	**Weekday 17-9, Weekend 0-24**
People (Person/m^2)	0.06	0
Lighting (Wm^{-2})	13	6.5
Equipment (Wm^{-2})	10	0
Ventilation (l/person)	11	0
Infiltration (m^3 s^{-1})	0.1	0.1
Heating: Set-point temperature (°C)	20	15
Cooling: Set-point temperature (°C)	26	off

Table 10.3. Main features of the green roof options used for running the simulations.

Green roofs' parameters	**Values**
Leaf Reflectivity	0.4
Leaf Emissivity	0.9
Minimum Stomatal Resistance (s/m)	180
Roughness	Medium
Soil thickness (m)	0.1
Conductivity of Dry Soil (W/m-K)	0.35
Density of Dry Soil (kg/m^3)	561
Specific Heat of Dry Soil (J/kg-K)	1061
Thermal Absorptance	0.9
Solar Absorptance	0.8
Visible Absorptance	0.6
Saturation Volumetric Moisture Content of the Soil Layer	0.4
Residual Volumetric Moisture Content of the Soil Layer	0.01

In particular, version 9.2 of the Energy Plus software has been used [28]. The results of the simulations were compared to the performances of a conventional roof. In the aim of assessing the behaviour of these very different components under equal conditions, the green roofs' components were arranged so that their thermal transmittance, referred to dry soil conditions, meets the thermal transmittance of the conventional roof.

10.3.B The weather conditions of analysed sites

As previously reported, the analysis of the study has been extended to 65 main Italian sites (see Fig. 10.2). On purpose, it should be noted that the territory of the Italian peninsula is characterized by very different climatic conditions, ranging from a relatively cool mid-latitude version of the continental climate, Dfa, typical of inland northern areas of Italy, to a Mediterranean climate profile, Csa, typical of coastal and Southern areas, in reference to the Köppen climate classification [29].

Specifically, the magnitude of climatic vector, *Vc*, has been used for describing the climate conditions of the analysed cities [30-32]. In this study, it was decided to consider for the heating season a period going from October15th to April 14th, while for the cooling season a period comprised between April 15th and October 14th.

Figure 10.2. Map of Italy with marked considered sites.

In addition, the values of *Vc* have been divided by square root of three in order to consider a value equal to one for localities with outdoor air temperature, outdoor specific humidity and solar irradiation corresponding to the average value of all the considered sites. Clearly in this way, the same weight is attributed to each of the three considered climatic parameters. The obtained results for $Vc/\sqrt{3}$ range from 0.67 to 1.48 in the heating season, and from 0.86 to 1.21 during the cooling season.

It should be here underlined that the sites in which the study has been conducted were selected in order to have climate conditions representative as much as possible of the

above-cited climatic variety, hence, allowing a reliable appraisal of the effect of the weather variability on the energy efficiency of the building envelope.

The climatic data used to run the simulations are those included in the EnergyPlus weather files database [28].

10.4 Results and Discussion

The simulations carried out for this work have led to the results shown in Fig. 10.3, with regards to the energy performance of the building. Specifically, Fig. 10.3 describes the behaviour of the EP index versus the variation of the Vc parameter for heating and cooling seasons as well as for the four roofing options (standard roof, cool roof, green roof with low LAI, and green roof with high LAI). Obviously, each analysed site is characterized by two different values of the Vc, one for the heating season and one for the for the cooling season.

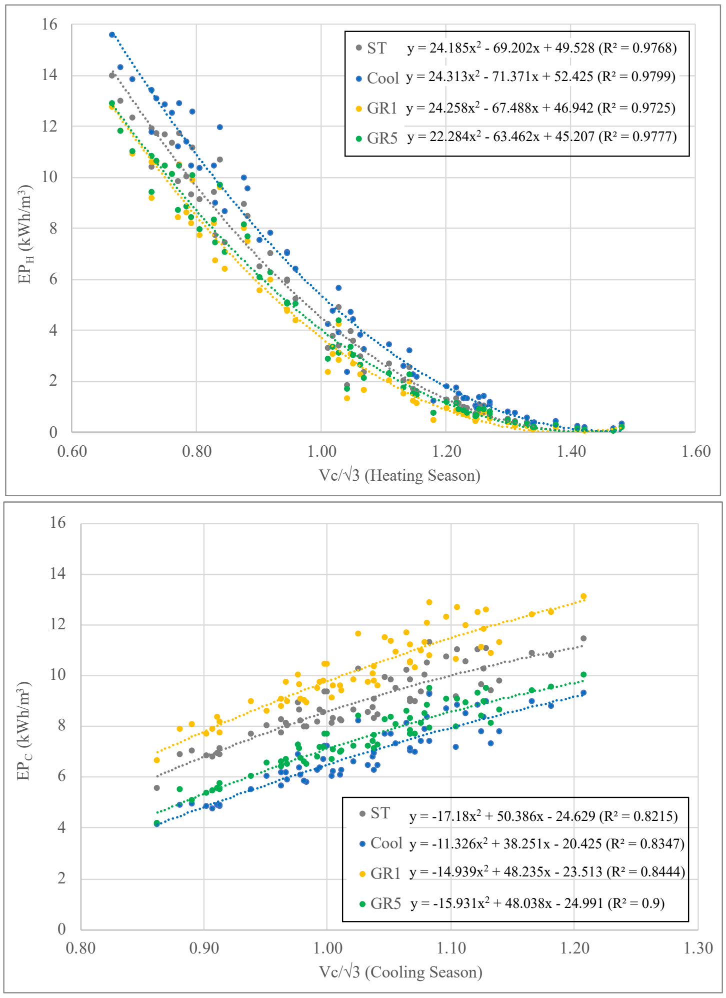

Figure 10.3. Comparison between the energy performances of the selected four roof options for heating (top) and cooling (bottom) seasons.

As shown in Fig. 10.3, for each roof option, data correlate quite well with a second order polynomial regression, indicating that an increase in Vc entails a reduction of the heating energy need during heating season, and an increase of the cooling energy need in the cooling season.

Moreover, the reported results confirm the main observations stated by La Gennusa et al. [27], namely that during the heating season, green roof options (with LAI values equal to 1 and 5) allow to reduce the heating energy needs, when compared to the standard roof, although for high values of *Vc* (heating season) this consideration fails.

Regarding, instead, the cooling season, as shown in Fig. 10.3, simulation results signal a general (smooth) trend according to which to an increase in *Vc* (cooling season) also corresponds an increase in the cooling energy needs for each roof option.

However, a consideration must be made about the green roofs characterized by low values of LAI. The fact that these roofing show a worse behaviour compared to the standard ones implies that only green roofs with higher values of LAI contribute to reduce the energy use for cooling. This consideration is attributable to the low level of foliage, which in turn determines a relatively less cooling effect due to the evapotranspiration and a somewhat small shading effect of the roof surface [27,33]. Moreover, this behaviour does not seem to be modified by the variations of *Vc* (cooling season), since the curves are not overlapped.

As for the indoor comfort performance of the building, as previously mentioned, the PMV index and the frequency with which the hourly PPD exceeded a 10% value for each site and for each roof options have been evaluated.

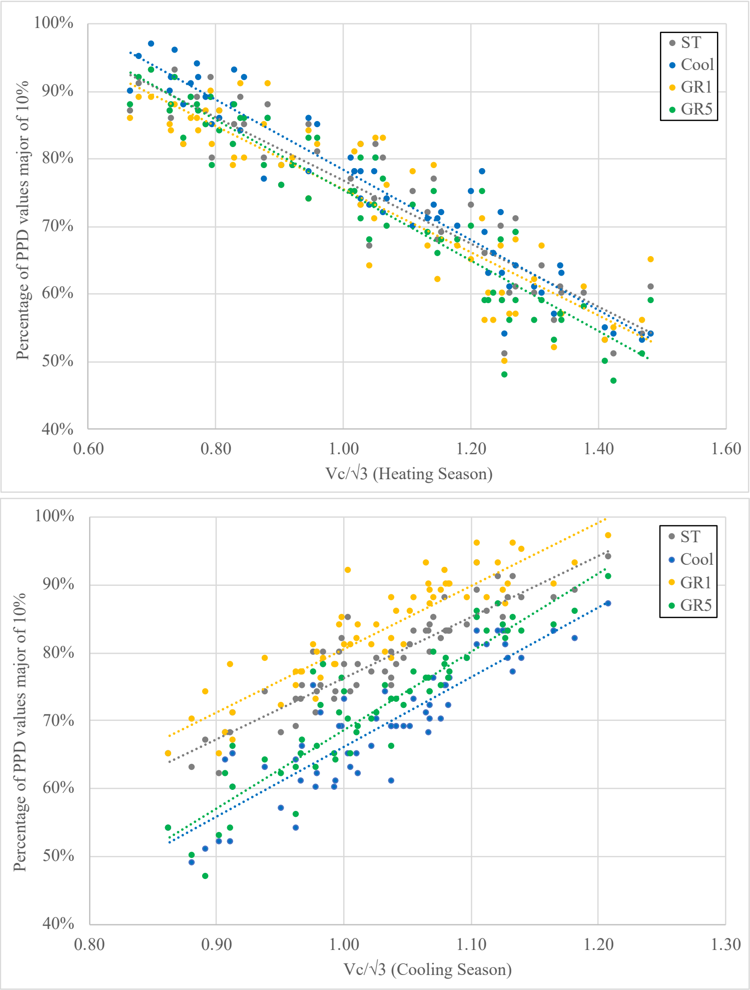

Figure 10.4. Percentage of PPD values greater than 10% for each site and for each roof option in the heating (top) and cooling (bottom) seasons.

The occurrences in which PPD values greater than 10% have been obtained, reported in Fig. 10.4, both for heating and cooling seasons, highlight that the analysed building is not suitable to be installed in every Italian locality. In fact, the Italian territory is marked by very different climate conditions. Moreover, the analysed building has large glazing surfaces that are generally used in cold climate and very rarely in warm climate: this could likely affect the results. Nevertheless, this building was utilized in the present work because it is recognized in literature as a benchmark model for Italian offices [23], also in order of clarifying the link between the indoor comfort levels and the building envelope itself. Even if the air-conditioning system maintains the indoor air temperature to a constant set point value, this is not a necessary and sufficient condition for guaranteeing the indoor thermal hygrometric comfort. Consequently, it is important to pay attention to the correct design of the building envelope, such as using innovative technologies as cool roofs and/or green roofs, which allow to reduce the roof surface temperature and, therefore, the indoor thermal radiative exchanges with the ceiling [34]. In addition, such solutions also contribute in reducing the Urban Heat Island effect, and thus the heat-related mortality during heatwaves [35,36].

The graphs reported in Fig. 10.5 show the behaviour of the average values of the PMV index during heating and cooling seasons for each roof options. Considering a comfort range given by PMV values comprised between -0.5 and 0.5 (which correspond to PPDs not greater than 10%), the graph displayed at the top of Fig. 10.5 points out that, for values of *Vc* (heating season) minor than 1.1, the PMV index essentially assumes average values falling out of the considered comfort range (minor than -0.5).

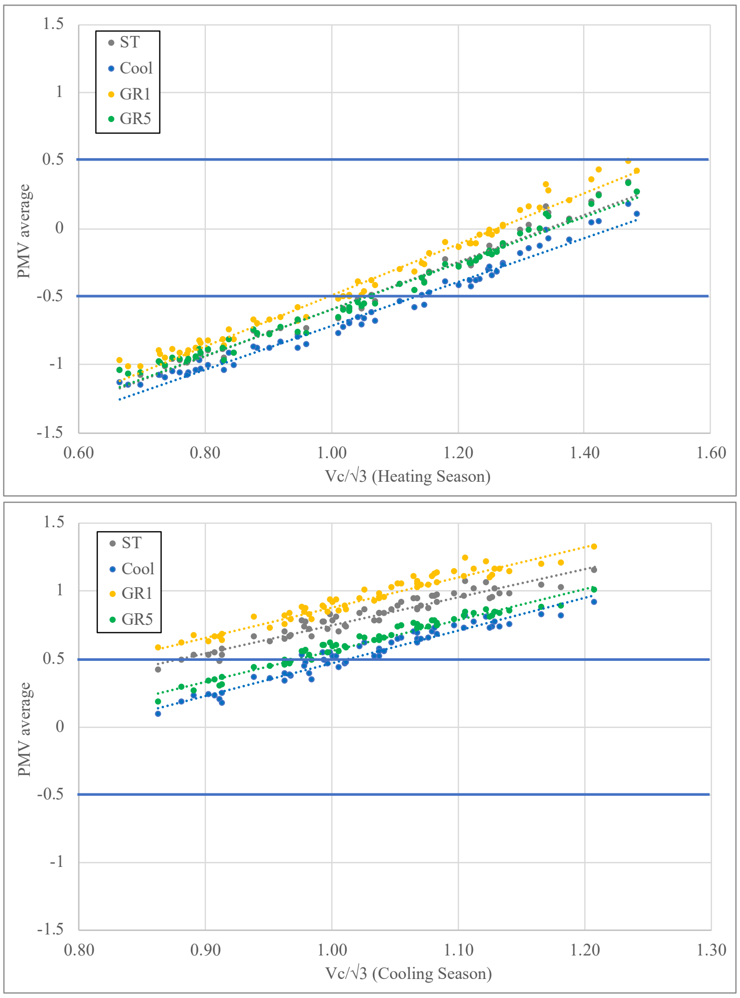

Figure 10.5. Average values of PMV for each site and for each roof option in the heating (top) and cooling (bottom) seasons.

On the other hand, the graph reported at the bottom of Fig. 10.5 highlights that, for values of *Vc* (cooling season) higher than 0.9, the PMV index typically assumes average values falling out of the considered comfort range (superior than 0.5), circumstance that involves almost all the considered sites.

10.5 Conclusion

The results reported in the discussion section of this work, have been obtained from energy simulations relative to a reference building, which has been hypothesized operating in 65 different sites located throughout Italy, going from the North to the South of the Country. The results point out that green roofs should be characterized by a high LAI value in order of being suitable as an envelope component able to improve both the energy performance and the indoor thermal comfort of the building. On the other end, cool roofs behave better during the cooling season for both the energy performance and the indoor comfort, with respect to other types of roofs; nevertheless, the building energy and indoor performances clearly worsen during the heating season.

Besides, further analyses are needed, particularly concerning the relationship between the indoor microclimate conditions and their effects on the energy performances of buildings, and on the risk of the so-called heat-related mortality. In fact, the more the thermal properties of the building envelope are improved, the more the heatwave resilience increases.

Chapter 10 Acknowledgment

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SECTION I.D – Results and Findings

From the results of this section the subsequent considerations can be made.

- About an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions:
    - the existence of a correlation between climatic vector V_C and Degree Days during the heating season (HDD) has been observed, while no correlation between V_C and Degree Days in the cooling season (CCD) seems to occur;
    - the greater the HDD is the greater the $Q_{Heating}$ is, but an opposite behaviour has been found in case of V_C, whereas as regards the cooling energy loads, a similar behaviour of V_C and CDD has been found (that is: the greater the CDD or V_C is the greater the $Q_{cooling}$ is);
    - green roofs result to be favorable with low HDD and high V_C;
    - green roofs result to be favorable with high CCD and low V_C.

- On the subject of comparing the indoor performances of a building equipped with different roof configurations in several Italian sites:
    - for each roof option, data correlate quite well with a second order polynomial regression, indicating that an increase in Vc entails a reduction of the heating energy need during heating season, and an increase of the cooling energy need in the cooling season;
    - during the heating season, green roof options (with leaf area index – LAI values equal to 1 and 5) allow to reduce the heating energy needs, when compared to the standard roof, although for high values of Vc this consideration fails;
    - during the cooling season, it has been observed a general smooth trend according to which to an increase in Vc corresponds an increase in the cooling energy needs for each roof option;
    - although the air-conditioning system is able the indoor air temperature to a constant set point value, this is not a necessary and sufficient condition for guaranteeing the indoor thermal hygrometric comfort.

PART I – Interventions on Single Buildings

SECTION I.E – Ramblings on the Pertinent Standards

In consideration of the fact that both public administrations and technical experts need reliable calculation methodology to assess buildings' energy performance, this section shows a comparative between the well-established EN ISO 13790 and the recently published EN ISO 52016 Sandards, with the aim of comparing the suitability of the two respective proposed simulation approaches in relation to their different levels of complexity and results' level of detail.
This section of the dissertation incorporates one chapter:

Chapter 11 - The European Standards for Energy Efficiency in Buildings: an Analysis of the Evolution with Reference to a Case Study

Chapter 11 - The European Standards for Energy Efficiency in Buildings: an analysis of the Evolution with Reference to a Case Study

This chapter consists in the following conference paper:
Cirrincione, L., Marvuglia, A., Peri, G., Rizzo, G., Scaccianoce, G., The European standards for energy efficiency in buildings: An analysis of the evolution with reference to a case study, (2019) AIP Conference Proceedings, 2191, art. no. 020049.
DOI: https://doi.org/10.1063/1.5138782

Abstract: The improvement of the energy efficiency of building stocks represents an important contribution for the reduction of the energy consumption in the European Union (EU), along with the decrease of greenhouse gases emissions. In this aim both the public administrations and the technical experts need reliable calculation methodology to assess buildings' energy performance. In this framework, despite the recent publication of the Standard EN ISO 52016, that deeply modifies the approach to the energy building simulation by introducing a new hourly dynamic calculation model, the current normative framework (EN ISO 13790) will maintain its validity until the incorporation of the new Standard in the national Standards and Decrees (such as the Italian Standard UNI/TS 11300-1) will take place. The aim of this paper is comparing the suitability of the simulation approaches proposed by the above-cited Standards in relation to their different levels of complexity and to the levels of details of the results provided by them. On purpose, a case study in which the energy behaviour of a public building, sited in the Sicilian city of Trapani in the South of Italy, will be analysed and the results of the simulations conducted according to the aforementioned Standards will be compared considering the outcomes of the EnergyPlus software as reference values.

Keywords: Building Energy Efficiency, European Standards, Building Simulation.

11.1 Introduction

According to the JRC Energy Report 2018 [1], the energy consumption in the building sector accounts for the 25.7% share of the total energy use in the EU-28, while the IEA Global Status Report 2018 [2] states for the same sector a 36% share of the final energy use (corresponding to a 39% of energy-related CO_2 emissions). Therefore, the improvement of the energy efficiency of building stocks represents an important contribution for the reduction of the high dependency from energy supplied by countries outside European Union (EU), along with the decrease of greenhouse gases emissions. The diminution of such dependence constitutes also a strong element of safety for the EU-28. In this aim both the public administration and the technical experts need reliable calculation methodologies able to assess the level at which the energy efficiency is achieved in the building sector, also in sight of awarding buildings with high performance environmental labels [3].

Loonen et al. [4] and Pieter de Wilde [5] have made general observations about the opportunities, strengths and challenges relative to the use of building performance simulation and analysis to support future innovation processes. In addition, simulations have also been conducted and analysed to compare different retrofit solutions to identify energy action priorities [6, 7] and to assess the price impacts of energy efficiency ratings on the building market [8].

The above-cited considerations led EU Member States to draw up a common energy policy in order to set up a suitable calculation methodology to assess buildings' energy performance [9, 10]. Despite the recent publication of the Standard EN ISO 52016 [11], that deeply modifies the approach to the energy building simulation by exclusively referring to the dynamic time-dependent regime (allowing for a more accurate evaluation of the energy performance [12, 13]), and that calls for the need of a more cognisant category of experts, the current normative framework (EN ISO 13790 [14]) will maintain its validity until the needed incorporation of the new Standard in the national Standards and Decrees (such as the Italian Standard UNI/TS 11300-1 [15]).

In this framework, many problems have arisen concerning the definition of energy ratings (based on operational or asset ratings) and the accuracy of the calculation methodology (simplified or detailed). In fact, as shown by various studies in recent literature, designers and researchers need suitable tools able to facilitate energy analysis in buildings, while still obtaining reliable results [16, 17, 18].

Simulation toolkit based on the EN ISO 13790 have been developed in several research case studies, by using simple methods such as Excel-based calculation tools [19, 20], or more sophisticated ones, namely MATLAB-based calculation codes [21, 22, 23]. In addition, when considering strategies for consumption reduction, tools like EnergyPlus [23, 24, 25] and TRNSYS [22] (using a transient method to simulate the building energy behaviour), have been used to validate the energy performances' results obtained by the application of the above-mentioned Standard, considering buildings under various climate conditions, and with multiple energy conservation measures being applied to them. In addition, algorithms to select the best combination of retrofit solutions for a building, taking also into account the costs, have been investigated [26]. As for the Standard EN ISO 52016, since we are actually in a transition phase, its application for research purposes has only recently begun to be taken into consideration. To date in [27] a calibration of the procedure described in the EN ISO 52016 was carried out by means of the results provided by the dynamic software TRNSYS adopting a black-box approach, referring to buildings located in the Mediterranean area.

In the present work the differences between the new Standard EN ISO 52016 and the EN ISO 13790 will be analysed by means of a case study in which the energy behaviour of a public building, sited in the Sicilian city of Trapani in the South of Italy, will be simulated. In particular, the results of the simulations conducted according to the aforementioned Standards will be compared, considering the outcomes of the EnergyPlus software as reference values. The final aim of the paper is comparing the suitability of the above-cited approaches in relation to their different levels of complexity and to the levels of details of the results provided by them, in order to provide professionals (designers and researchers) with considerations regarding whether it is convenient to keep using the EN ISO 13790 or start utilizing the EN ISO 52016 during the transition phase.

11.2 Comparison between the EN ISO 13790 and the EN ISO 52016 Standards

The hourly calculation method proposed by the EN ISO 52016 [28] is a revised, and more advanced, method than the simplified hourly one given in EN ISO 13790 [14]. The main difference is that the building elements are not aggregated to a few lumped parameters, but kept separate in the model, as shown in Figure 11.1.

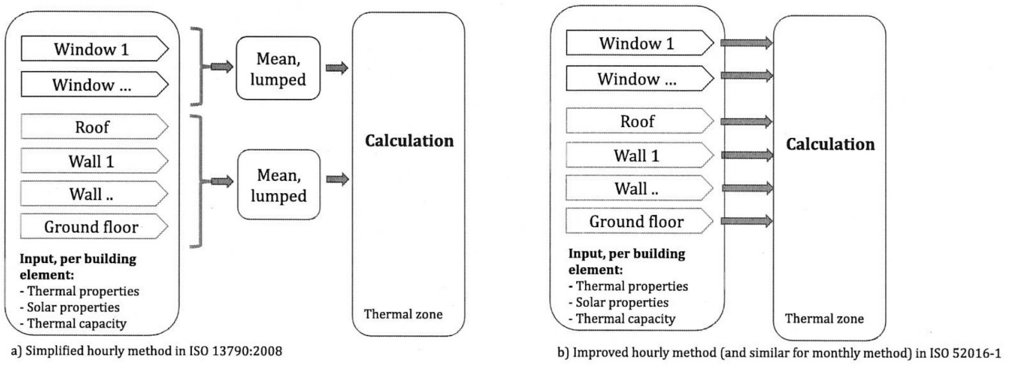
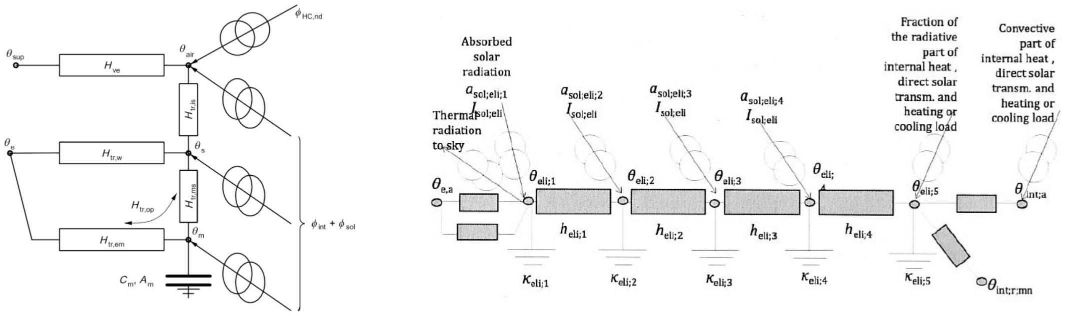


Figure 11.1. Simplified method in EN ISO 13790 (a) compared to improved hourly method in EN ISO 52016 (b) [28].

Specifically, the EN ISO 52016 uses a more complex and an extensive RC network thermal model for each building element separately, that is considering five nodes per building element and a capacitance for each building element inside a thermal zone – instead of using a 5R1C model, as in the EN ISO 13790 – to perform the hourly calculation relative to the energy loads and needs for heating and cooling and the hourly indoor temperature (air, mean radiant and operative). Figure 11.2 shows a comparison between the two models.



(a) (b)

Figure 11.2. Comparison between the 5R1C model of the EN ISO 13790 (a) [14] and the improved RC network thermal model of EN ISO 52016 (b) [28].

As a consequence, this leads to a number of advantages, in particular that the properties of each building element remain individually known, instead of being aggregated to only two thermal resistances, which makes the model more transparent and more widely usable compared to ISO 13790. Some advantages (which make the method better suited to deal with passive solar energy and other techniques, as requested by the EPB Directive [10] on the energy use and the thermal performance of buildings and building elements) and drawbacks of the method proposed by the EN ISO 52016 are given in Table 11.1.

Table 11.1. Advantages and drawbacks of the EN ISO 52016 model, with respect to the EN ISO 13790 model [28].

Advantages of the EN ISO 52016 model	Drawbacks of the EN ISO 52016 model
There is no worry about how to combine e.g. the heat flow through the roof and through the ground floor, with their very different environment conditions (ground temperature and ground inertia, solar radiation on the roof).	The model requires higher inputs of building properties and dimension which may not be available all the time.
The thermal mass of the building or building zone can be specified per building element and there is no need for an arbitrary lumping into one (mean) overall thermal capacity for the building or building zone.	Due to the much higher number of nodes a robust numerical solution method (software) is required when considering a whole building - the solving of the matrix needs to be done by programming (the rest of the calculation can still be done in a spreadsheet).
The mean indoor surface temperature (mean radiant temperature) can be clearly identified and kept distinct from the indoor air temperature	

Furthermore, the EN ISO 52016 also contains a specific hourly method to calculate the moisture and latent energy loads, and needs, for humidification and dehumidification and the hourly indoor air moisture content (i.e. humidity), making it possible to predict the dynamic behaviour of a building in a way more similar to the one provided by the sophisticated software products, like EnergyPlus.

In addition, the possibility of taking into account in a more detailed way the hourly/daily variations in weather conditions, their dynamic interactions with technical buildings systems, control aspects and boundary conditions (where relevant for the calculation), represents a further advantage, with respect to the EN ISO 13790, allowing to use the model as a simulation tool to put in act both design and control strategies relative to the building's technical systems.

It must be underlined that, despite the fact that the EN ISO 52016 hourly calculation method constitutes a more powerful instrument than its predecessor EN ISO 13790, it still requires the same input data from the user, so that a limited access to input data is no reason to choose a simpler calculation tool.

11.3 Materials and Methods

Not a lot of research work has been done on the hourly dynamic calculation model provided by the EN ISO 52016 [28], being it a recently published Standard and considering the fact that its use is not mandatory yet. Thus, the aim of the case study presented in this work is to test the accuracy of the aforementioned model by comparing it with the, still in force, 5R1C model of the EN SO 13790 [14], considering the outcomes of the EnergyPlus software as reference values. Specifically, the numerical simulation models of the two Standards, EN ISO 13790 and EN ISO 52016, have been implemented in the MATLAB environment.

To this purpose, the differences between the two Standards will be analysed by means of a case study in which the energy performance of a public building will be simulated. The building in question is the city Hall of the Sicilian city of Trapani in the South of Italy, whose general characteristics are reported in Figure 11.3. Given its position, the city of Trapani is characterized by a Mediterranean climate profile, typical of Italian coastal and Southern areas.

Position: Trapani (TP)
Latitude: 38°01'01"
Longitude: 12°30'48 "
Altitude: 14 m a.s.l.
Climate zone: B
Degree days: 810
Building typology: Office
Construction year: 1904

Figure 11.3. General characteristics and south-east elevation view (on the left) of Trapani city Hall building.

The city Hall building has a covered area of about 2000 m^2 and consists of four storeys above the ground, resulting in a total volume of about 6700 m^3. The interior plan layout of the typical floor is structured around a central light-well court. The building is completely isolated on all four sides and presents the typical construction characteristics of the era in which it was built, therefore without any attention to energy saving solutions. In particular, the main structure consists of load-bearing masonry walls, made up of natural limestone ashlars and wooden floors, while the windows are of the single-glass type with wooden frames and shutters without solar shadings.

The input boundary conditions for all three simulation approaches were made as close to each other as possible. In particular, set-point temperatures of the building for the heating and cooling of 20°C and 27°C, respectively for winter and summer seasons, were assumed. As for the main thermo-physical properties of the building's opaque and glazed elements, these are reported in Table 11.2, and have been mainly obtained using the UNI/TR 11552 [29].

Table 11.2. Thermo-physical properties of the elements of the considered building.

Building element	**Typology**	**Thickness (m)**	**Thermal Transmittance (W/m^2°K)**
Masonry wall - 1st and 2nd floor	Opaque	0.54	0.90
Masonry wall - 3rd and 4th floor	Opaque	0.34	1.341
Roof slab	Opaque	0.06	1.18
Floor slab	Opaque	0.455	1.622
Windows (single glass)	Glazed	0.005	5.835

Regarding, instead, the functioning of the building in terms of internal heat gains related to thermal comfort [30, 31], occupancy, lighting, equipment, ventilation and infiltration, it was decided to adopt values (and relative schedules) based on those reported in the studies conducted by Corgnati et al. [32, 33] and Fabrizio et al. [34] on medium-sized office buildings. The adopted values are reported in the following Table 11.3.

Table 11.3. Internal heat gains' adopted values and relative schedules for the considered building [32, 33].

Internal heat gain element (unit)	Adopted value	Element schedule	
People (Person/m^2)	0.06	9:00-17:00 Monday to Friday	
	0	17:00-9:00 Monday to Friday	0:00-24:00 Saturday and Sunday
Lighting (W/m^2)	13	9:00-17:00 Monday to Friday	
	0.065	17:00-9:00 Monday to Friday	0:00-24:00 Saturday and Sunday
Equipment (W/m^2)	10	9:00-17:00 Monday to Friday	
	0	17:00-9:00 Monday to Friday	0:00-24:00 Saturday and Sunday
Ventilation (l/person)	11	9:00-17:00 Monday to Friday	
	0	17:00-9:00 Monday to Friday	0:00-24:00 Saturday and Sunday
Infiltration (m^3/s)	0.1	always	

As concerns the weather climatic conditions, those considered to perform the simulations are the ones relative to the Trapani-Birgi meteorological station, indicated in the EnergyPlus database [35].

Regarding the HVAC system it was decided to consider for both the EN ISO 13790 model and the EN ISO 52016 model an ideal one capable of maintaining the internal temperatures within the set point temperatures range. For consistency, an ideal HVAC system ("IdealLoadsAirSystem") was also considered in the EnergyPlus simulation.

11.4 Results and Discussion

In the following, the outcomes of the different simulation approaches defined in the previous section will be shown and analysed, in order to make a comparison.

Specifically, the main results of interest for the presented case study are represented by the monthly heating and cooling energy needs, which have been summarized graphically in the following Figure 11.4 and Figure 11.5.

Looking at Figure 11.4, showing a comparison amongst the heating energy needs results obtained from the three calculation models, it is evident how all three models present a similar monthly trend.

As regards instead the comparison relative to the cooling energy needs, reported in Figure 11.5, results show that the gap between the EN ISO 13790 model and the EnergyPlus reference values is much more limited respect to the one relative to the EN ISO 52016 model results. This latter gave, in fact, a substantial overestimation of the cooling needs. This could be due to different reasons, the first one concerning the way in which this model calculate the internal solar gains, and in particular the allocation between the two components radiative and convective. Such aspect is indeed particularly relevant for the climate context considered. A second aspect which could contribute to such discrepancy in the results is related to the way the HVAC system comes into operation when the temperatures returned by the calculation models fall out of the optimal range. In particular; in the case of the EN ISO 13790 model the set point temperatures are compared with the air temperatures returned by the model, while in the EN ISO 52016 model this comparison is made with the operative temperatures. After all, the current sensors that enable the HVAC on-off regulation are all driven by the air temperature and not by the operative one.

Comparing, instead, Figure 11.4 with Figure 11.5 it can be seen how the heating needs result very low (reaching zero) during summer, thanks to the high radiation and external air temperature and, accordingly, quite higher cooling energy needs occur. Similar considerations can be drawn for the winter needs.

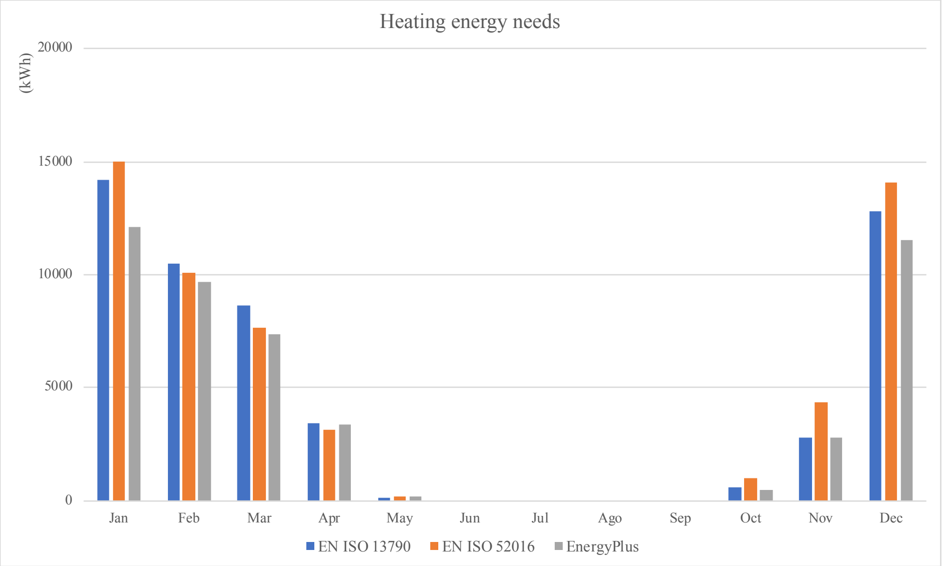


Figure 11.4. Comparison amongst the heating energy needs results obtained from the three calculation models.

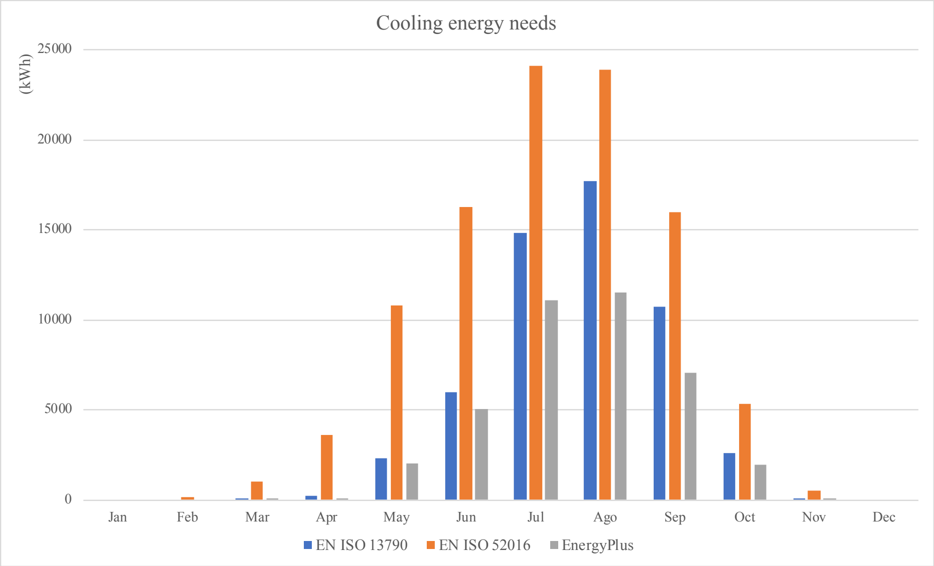


Figure 11.5. Comparison amongst the cooling energy needs results obtained from the three calculation models.

The above-mentioned differences, which could have been expected, between the two Standards are ascribable to the intrinsic definition of the two models proposed by them. The inputs for the EN ISO 13790 5R1C model are less compared to the EN ISO 52016 extensive RC network model as the elements are lumped to a few parameters, which increases the uncertainty in the dynamic simulation of the building. In fact, the improved calculation method introduced by the EN ISO 52016 allows to model a more advanced dynamic behaviour considering the contributions from each nodes of the building elements. Thus, the EN ISO 52016 model should derive more accurate results and could give a dynamic behaviour considerably different from the previous Standard.

However, on the basis of the obtained results and of the above considerations regarding the differences between the two Standards, it is evident how some aspects of the EN ISO 52016 should be analyzed and investigated more thoroughly as future research studies. In particular, (i) the new approach used to calculate the thermal storage capacities of the single elements and (ii) the distribution of the solar gains between the radiative component and the convective component seem to be the aspects on which greater attention will have to be paid.

11.5 Conclusion

The comparison between the EnergyPlus reference values and the results obtained from the models relative to the two considered Standards, object of the presented case study, suggest that for the considered context both the EN ISO 13790 model and the EN ISO 52016 model seem to be consistent with the EnergyPlus reference values in relation to the heating energy needs. While, concerning the cooling energy needs the EN ISO 52016 model makes a significant overestimate.

The presented case study represents a first investigation in the field, as a future development it can be deepened by extending the simulation models to multiple thermal zones, taking into account different usage and boundary conditions for separate parts of the investigated building, and by also including detailed HVAC system as well. Moreover, as a further step, it would also be useful to discuss the simulation results in terms of final energy utilization; in fact, considering that the energy market is being projected towards an electrification also at European level, it could be advisable to investigate the economic aspects.

Therefore, buildings' energy performance analysis can be used as a decision-making support tool in the development of innovative materials for energy efficiency in the building sector; moreover, it also represents an enabler for the proper design, construction and operation of buildings, especially when the expectations of a wide range of stakeholders need to be meet. In this aim both the public administration and the technical experts need reliable calculation methodology (easier to use compared to complex dynamic simulations) to assess buildings' energy performance with sufficient accuracy.

In conclusion, the cooperation between public administration, technical experts and researchers working on simple but yet reliable energy performance calculation methodologies, is essential in order to improve the energy efficiency of the building sector. Such aspect is, indeed, of paramount importance for the reduction of the high dependency from energy supplied by countries outside European Union (a strong element of safety for the EU-28), along with the decrease of greenhouse gases emissions.

Chapter 11 Acknowledgment

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SECTION I.E – Results and Findings

Thanks to the analysis carried out in the case study part of this section, some remarks about the considered European Standards for energy efficiency in buildings can be pointed out:

- that the gap between the EN ISO 13790 model and the EnergyPlus reference values is much more limited respect to the one relative to the EN ISO 52016 model results;
- the improved calculation method introduced by the EN ISO 52016 allows to model a more advanced dynamic behaviour;
- the inputs for the EN ISO 13790 5R1C model are less in number compared to the EN ISO 52016 extensive RC network model, as the elements are lumped to a few parameters, condition which seems to increase the uncertainty in the dynamic simulation of the building;
- for the considered context both the EN ISO 13790 model and the EN ISO 52016 model appear to be consistent with the EnergyPlus reference values in relation to the heating energy needs, while concerning the cooling energy needs the EN ISO 52016 model makes a significant overestimate.

PART I – Conclusion

In this first part of the dissertation a few solutions aimed at consuming less energy, ensuring the indoor thermal comfort conditions for the occupants and improving the environmental performance of buildings were presented.

The main results and findings, which were briefly summarized at the end of each section, will be further discussed in the ambit of the general context of the dissertation in the conclusive Part IV.

The outcomes of such studies allowed to assess the feasibility of the proposed interventions in accomplishing a better mitigation and adaptation to the climate change scenario from a single building standpoint.

As a further research step, in the next part of the dissertation, the spatial scale at which some of the proposed solutions can be applied will be enlarged to a group of buildings, in order to consider how such condition may influence the energy efficiencies of the respective surrounding areas.

PART II – Interventions on Cluster of Buildings

In this part of the dissertation the matter regarding the energy efficiency and the environmental performance is treated from a wider point of view, i.e. analysing the resilience potential of clustered group of buildings, besides the single building itself.
The main aim is being able to quantify and assess the cumulative effects of some energy efficiency solutions when simultaneously installed on buildings located close to each other, which can also bring a contribution in helping stakeholders in the planning of cities' energy interventions, also in the light of recently issued European directives.
Specifically, it was decided to consider three typical urban contexts as emblematic of the condition of "cluster of buildings", namely a university campus, a district of a metropolitan city (the district Bandita of the city of Palermo) and a small village (Esch-sur-Alzette in Luxembourg).
This part of the dissertation is composed of two chapters:

Chapter 12 - Fostering the energy efficiency through the energy savings: the case of the University of Palermo

Chapter 13 - How effective will vegetated roofs be in enhancing buildings' climate resilience in 60 years?

Chapter 12 - Fostering the energy efficiency through the energy savings: the case of the University of Palermo

This chapter consists in the following conference paper:
Bisegna, F., Cirrincione, L., Lo Casto, B.M., Peri, G., Rizzo, G., Scaccianoce, G., Sorrentino, G., Fostering the energy efficiency through the energy savings: The case of the University of Palermo, (2019) Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, art. no. 8783774.
DOI: https://doi.org/10.1109/eeeic.2019.8783774

Abstract: This paper reports the strategy implemented by the Palermo University (Italy) aimed at fostering the energy performance of its campus, particularly towards financing energy saving measures. The basic idea is that the money saved through the energy efficiency actions, constitute the main flywheel to fund further savings and energy efficiency interventions. Results of this paper might bring a useful contribution to the energy planning of cities, since campuses may be regarded as emblematic case study of what can be done in cities because they reproduce, at a little scale, the functioning of wider urban contexts.

Keywords: university campus, energy saving, low-carbon, energy efficiency.

12.1 Introduction

The European Union (EU) is strongly committed to promoting a smart, sustainable, and inclusive growth, as well declared in the Europe 2020 Strategy [1]. In particular, with respect to the sustainability aspect of growth, EU intends to develop a more competitive low-carbon economy also characterized by an efficient and sustainable use of resources. In this regard, among the objectives set out in the Europe 2020 Strategy, the so-called "20/20/20" targets are certainly worth of mention; in detail, the 2020 climate & energy package establishes three main objectives: 20% cut in greenhouse gases (GHG) emissions (from 1990 levels), 20% of EU energy from renewables, and 20% improvement in energy efficiency. The seventh Environment Action Program (EAP) [2], which aims to guide European environment policy until 2020, shall guarantee the achievement of these 2020 climate and energy targets by the EU, and that the EU is working towards reducing its GHG emissions by 80–95 % compared to 1990 levels. Such a challenging reduction of GHG emissions has been established indeed as a milestone for the 2050 in the EU Roadmap for moving to a competitive low carbon economy [3]. For the period going from 2021 to 2030, the EU has set out the following objectives, which are included in the 2030 climate and energy framework [4]: at least 40% cuts in GHG emissions (from 1990 levels); at least 32% share for renewable energy; and at least 32.5% improvement in energy efficiency.

In the Roadmap, for moving to a competitive low carbon economy [3], it is clearly expressed the necessity to put more focus on energy efficiency policies and Member States are called to rapidly put forward national low carbon Roadmaps. In order of achieving the above-cited targets, the EU strongly believes in the opportunity deriving also by the building sector, particularly by the improvement of the energy performance of buildings. In this regard, the involvement of Best Available technologies could be useful for this purpose [5], clearly, never overlooking that energy efficiency requirements should be attained without compromising indoor thermal comfort conditions to the occupants [6]. In the Roadmap [3], on one hand, the significance of attaining the objective of the recast Directive on energy performance of buildings (i.e. EU/2010/31) [7], stating that new buildings built from 2021 ahead will have to be nearly zero-energy (NZE) buildings, is stressed out. On the other hand, the refurbishment of existing buildings, and in particular the manner in which financing the necessary investments, is recognized as an even tougher challenge [8].

In this framework, university campuses together with their buildings have increasingly gained a lot of attention and concerns because they have been shown to spend a large amount of energy; pertinent literature reports indeed data of average energy consumption per unit area up to 797 kWh/ (m^2 year) [9]. In fact, typically, university campuses include buildings devoted to research and educational purposes (such as classrooms, offices and laboratories) as well as for living and cultural participating activities within the campus (such as dormitories, restaurants, shopping and sport facilities). Consequently, different energy use profiles characterize university buildings and, not always, such areas use the energy efficiently. As a result, in the last years, energy policies regarding university campuses have been reviewed deeply particularly looking at their energy efficiency and the energy sources feeding them.

The theme of the energy use in university campuses and the improvement of their energy efficiency has widely been investigated. In literature, studies reporting the strategies toward achieving sustainable campuses put forward worldwide are present. The work carried out by Yoshida et al. [10], for instance, reports the Osaka University experience. In detail, the energy efficiency strategy essentially consists in regulating the energy system according to people’s daily routines, using the plan–do–

check–act cycle, and outsourcing energy management to an ESCO (Energy Service Company). Furthermore, investigations on potential retrofit scenarios for existing campuses are present in literature. Wiryadinata et al. [11], for instance, analyse three different options (i.e. biomass-based system, combination of biomass and electrification, and electrification alone) to attain by 2025 carbon neutrality of the University of California, Davis (UCD), whose business-as-usual campus energy system is based on fossil-fired electricity and natural gas heating use. Among the options for sustainable and reliable energy, studies exploring the possibility to deploy microgrids, also in university campuses, are present. For instance, Husein and Chung [12] propose a model that aims to analyse both the technical and financial feasibility of a microgrid at the campus in Seoul National University. The evaluation of the level of sustainability of existing university campuses has also been addressed and indicators to be used as a reference to articulate or develop sustainable campus strategies have been introduced. For instance, Chen et al. [13] report 28 sustainable campus indicators introduced in Taiwan, covering policy management, buildings and equipment, and educational activities, which have been established using the fuzzy Delphi expert decision-making approach. There are also studies proposing models for predicting energy use of university buildings. A single mathematical equation for forecasting daily electric energy use of university buildings, especially to predict daily, monthly and yearly energy consumption of two different types of buildings, i.e, administrative and academic, located at the Southwark Campus of London South Bank University in London, has been developed using the Multiple Regression technique [14]. Furthermore, the impact of certain factors on energy consumption of campuses has been investigated. Song et al. [15], for instance, assess the impact of course timetabling on energy consumption in classrooms and propose an algorithm able to identify the best timetable in terms of energy use. Studies discussing the most suitable approach to adopt when evaluating the potential of energy use reduction of university campuses are also present. For instance, Nagpal and Reinhart [16], starting from the consideration that small campuses may effectively use the traditional approach for building energy modelling to study retrofit scenarios - while this approach does not seem to be feasible for larger campuses -, present two separate urban energy models to evaluate future energy scenarios of the campus of the Massachusetts Institute of Technology. The importance of a fully understanding of energy use characteristics of university buildings as a prerequisite for an appropriate energy planning of campuses is underlined as well. Guan et al [17], for instance, identify as a significant barrier for the energy planning of university campuses, the insufficient gathering of energy use data, and propose a methodology to examine the main features of energy usage of a Norwegian university campus.

Palermo University campus has also taken some steps for making its campus more sustainable. This paper, after briefly describing the energy saving measures already put forward, intends to discuss the financing scheme planned to be implemented by the Palermo University for fostering the energy efficiency of its campus.

12.2 The "Cittadella" of the University of Palermo

12.2.A Main features of the "Cittadella" campus

The "Università degli Studi" of Palermo accounts for approximately 41,000 students and is comprised of five Schools, more than 100 degree courses, and 20 Ph.D. courses.

The so-called "Cittadella" (i.e. "small town") campus is site of Departments mainly devoted to scientific and technology studies and researches. Large boulevards, which link more than 20 main buildings, characterize such a big Campus (nearly 37 hectares) hosting, apart from Departments, also laboratories, hostels, bars, refectories, printing centres, and a kindergarten.

Approximately 20,000 people daily attend the area, causing a high request of energy: nearly 20 GWh/year of primary energy is requested to satisfy the activities of such amount of users.

12.2.B An integrated index of the energy performance

A detailed analysis of the energy behaviour of the buildings belonging to the campus is certainly important in order of actuating specific restoration actions. Anyway, like for all the complex systems, one would need to get a unitary and integrated judgement of the performance of the site. In this regard, the application of the Campus Demotechnic Index (CDI) might usefully provide a comprehensive evaluation of the energy performance of the campus. This index derives from the Demotechnic Index proposed by Mata et al. [18], afterwards modified by Vance and Boss, in order to be specifically used as an energy index for US colleges and universities [19]. The CDI index is defined as the ratio of the total technological energy (ET) consumption of a campus – for the built environment and the campus mobility - to the total basal energy consumption (EM), i.e. the amount of energy consumed by 1 person over 1 year (typically, 3.57 GJ) multiplied by the campus population [19]. Energy generated from renewable or other non-carbon-based sources (solar, wind, hydro-electric, geothermal, and nuclear) was not included in CDI calculations. Generally speaking, values of CDI could vary from 0 to ∞.

The computed value of the CDI index for the campus considered here is 1.122, being the energy consumption per student equal to 3.54 GJ/person. A value of CDI close to 1 signals that part of ET is provided by non-fossil fuel-based energy, as actually is the case, since the campus is equipped with some solar photovoltaic plants for the production of electric energy. Moreover, the energy consumption for mobility has been neglected, since almost no students live inside the campus, despite spending nearly one-third of their time inside the campus.

Integrated efficiency indexes, like CDI, are certainly useful for a total judgement about the performances of a given campus enclave. Anyway, when specific energy actions are planned, such parameters are not very effective. In this case, in fact, a closer look to the performances of the single components of the campus would provide a better piece of information, allowing the identification of a priority list of interventions.

12.3 Realized energy saving actions

As previously mentioned, the University of Palermo has undertaken a significant policy aimed at the decarbonisation of the campus energy consumption. This policy encompasses the installation of plants for the generation of energy from renewable sources and the adoption of measures devoted at enhancing the energy efficiency of the campus' building stock. The construction of new photovoltaic energy systems, the installation of green roofs and the implementation of actions regarding the street lighting and the mobility are the most relevant interventions in this sense.

12.3.A Green roofs on a Department building

In the year 2015, three planted areas were set on the roof of the Department of Energy (Fig. 12.1). The coverages were layered, from bottom to top, with a waterproofing and anti-root element, a drainage component, a water storage element, a filter and soil. Five different vegetated species were planted: *Phila Nordiflora*, *Gazania Uniflora*, *Gazania Nivea*, *Sedum*, *Mesembryanthemum Barbatus* and *Aptenia Lancifolia.*

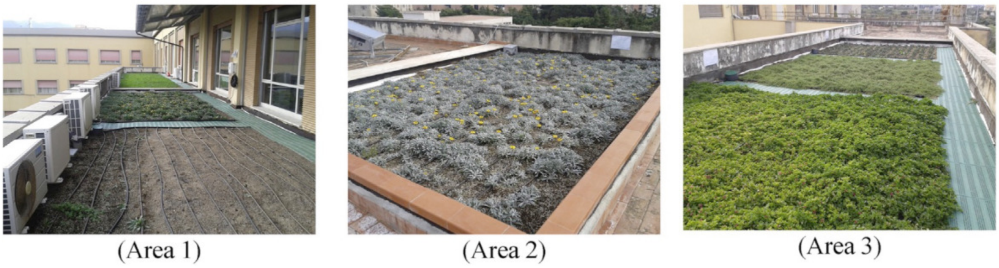

(Area 1) (Area 2) (Area 3)

Figure 12.1. Three vegetated coverings on a campus building.

The main purpose of these installations was to carry out a research aimed at assessing the thermal exchanges among the canopies and the soil. Anyway, this setting has generated a small decrease in the energy demand of the building hosting the green roofs. The benefit accounted for only a 2.5% decrease indeed, as shown in

Fig. 12.2. This corresponds to approximately 0.2 tons of avoided CO_2 emissions. Nonetheless, it contributes to addressing the building, and therefore the campus, towards a better sustainable path (Fig. 12.2).

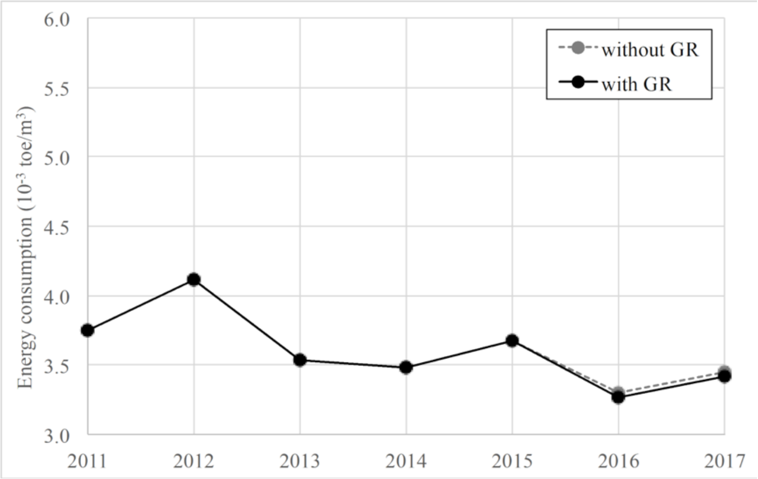


Figure 12.2. Trends of energy consumption of the campus building with and without the three vegetated coverings (GR= green roof).

Clearly, despite being small-sized, such green areas are also capable of capturing a small quantity of GHGs [20], and this represents another indirect benefit of these building components: it is well known, in fact, that a large diffusion of such roofing systems in urban contexts might reduce the Urban Heat Island effects [21].

12.3.B Photovoltaic system on the coverage of a Department building

As regards the use of Renewable Energy Sources (RES), a large photovoltaic plant (740 m^2 of panels) has been installed on the coverage of another Department building (Fig. 12.3). Its peak power accounts for 101 kWp, allowing a yearly electric energy production of about 140 MWh; this in turn determines a 74 tCO_2/year emission saving in the atmosphere (being 0.531 tCO_2/MWh the average emissions for the current electric Italian energy mix).

Figure 12.3. The large PV system on the coverage of a university building.

The installation of the PV plant has covered about 17.1% percentage of the building energy demand, from the year 2014 when the PV plant started operating (Fig. 12.4).

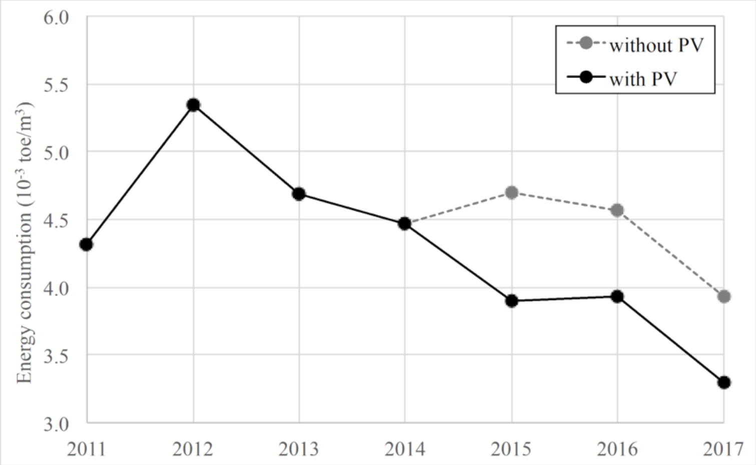


Figure 12.4. Trends of energy consumption of the campus building with and without the PV plant.

12.3.C Action concerning street lighting and mobility

In the recent years, the old street lighting network of the campus has been interested by an important action of renovation, essentially regarding the installation of new lighting poles. The 191 old high-pressure sodium (HPS) streetlamps were characterized by an installed power of up to 400 W. Recently, 51 of these 191 poles have been replaced with LED lamps with a power of up to 240 W, equipped with a system that is aimed at regulating their luminous flux. Such a large replacement has determined a reduction of approximately 42,000 kWh of electric energy, corresponding to a total percentage of 18%.

In addition, the mobility has been object of interest, with the aim of addressing the campus toward a less carbon energy path. The electric energy produced by the above-cited PV plant has been partially used for feeding charging stations for the electric mobility (Fig. 12.5). This represents only a demonstrative installation now; anyway, the University is deeply mindful of the theme of the green and sweet mobility, as the large parking of electrical bikes that students daily use also testifies.

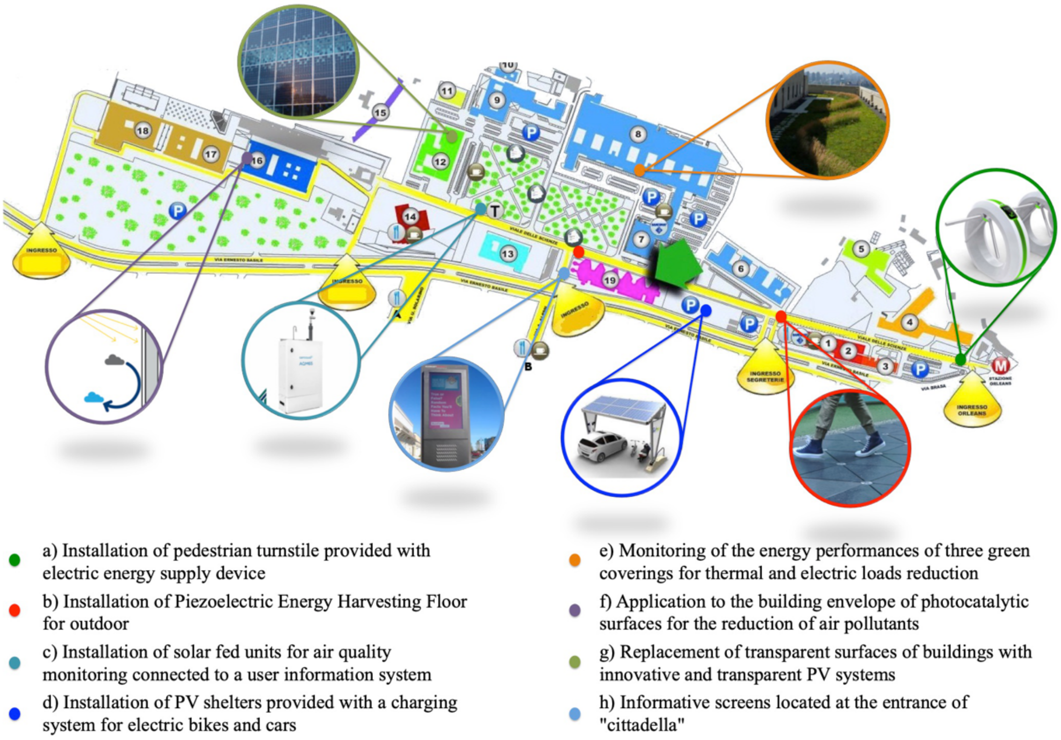
Figure 12.5. An energy charging station fed by a PV plant.

12.4 Fostering energy efficiency with savings

Apart from the actions directly inducing an energy saving (green roofs), or a production of renewable energy (photovoltaic plants), the University of Palermo has undertaken a virtuous policy aimed at generating an efficiency flywheel, financed by the already implemented energy saving measures. Among these actions, it must be contemplated the adhesion to the free market of the electric energy in Italy that might induce significant economic savings, thanks to the lower cost of the electric energy unit, which can be achieved through the market negotiation.

The University of Palermo, for example, taking advantage of the Italian free market of the electric energy, which permits to negotiate the price of the purchased energy, has changed its electric energy supplier, in this way realizing in the year 2014 a saving of 650,000 €, thanks to the related reduction of the energy bill. Part of this saving will be re-invested in actions that will produce further energy and, therefore, monetary savings, due to the positive feedback of the implemented interventions. Among these actions, financed with the monetary savings and considered for further intervention, it is relevant to note that mainly those capable of enhancing the quality of services provided to students are under examination. A list of these further actions totally financed by the revenues of the already adopted measures and interventions, comprises: the installation of PV shelters provided with a charging system for electric bikes and cars; the utilization for the building envelope of photocatalytic surfaces for the reduction of air pollutants; the replacement of the transparent surfaces of buildings with innovative and transparent PV systems; the implementation of an innovative system of info-mobility for smart-phones, the improvement of the environmental habits of the transfers from and to the University campus; the installation of piezoelectric energy harvesting floors and car flow monitoring; and the installation of solar fed units for air quality monitoring connected to a user information system.

Fig. 12.6 illustrates the allocation of the selected tools and equipment in the campus area: clearly, the choice of interventions to be implemented, particularly those not assigned to companies within an ESCO scheme, is mainly guided by the evaluation of their economic benefits in terms of their payback time.



● a) Installation of pedestrian turnstile provided with electric energy supply device

● b) Installation of Piezoelectric Energy Harvesting Floor for outdoor

● c) Installation of solar fed units for air quality monitoring connected to a user information system

● d) Installation of PV shelters provided with a charging system for electric bikes and cars

● e) Monitoring of the energy performances of three green coverings for thermal and electric loads reduction

● f) Application to the building envelope of photocatalytic surfaces for the reduction of air pollutants

● g) Replacement of transparent surfaces of buildings with innovative and transparent PV systems

● h) Informative screens located at the entrance of "cittadella"

Figure 12.6. Description of the group of tools and equipment financed with the attained energy saving.

The hypothesized actions can be grouped in three main categories: actions aimed at the production of energy by installing RES systems; interventions intended to enrich the basic equipment of the campus, being capable, despite not directly linked with a generation or a saving of energy, of attributing to the campus a higher quality of the services provided to students and workers; and interventions that aim to mitigate the GHG emissions and air pollution. Table 12.1 synthetically reports the main characteristics of the proposed interventions, in terms of economic and energy performances. Specifically, the table indicates the cost of the interventions, along with the saved yearly amount of energy, by dividing the action in the three above cited categories.

Table 12.1. List of the equipment and interventions financed with the energy savings.

	Planned measures	**Category of interventions**			**Measure cost (€)**	**Produced or saved energy (kWh$_e$/y)**	**Saved energy cost (€/kWh)**	**PBT (y)**
		RES	***Monitoring actions***	***GHG and pollution mitigation***				
a	Installation of pedestrian turnstile provided with an electric energy supply device		X		26,000	-	-	-
b	Piezoelectric energy harvesting floor	X			70,000	66,000	1.06	4.4
c	Installation of solar fed units for air quality monitoring, connected to a user information system		X		50,000	-	-	-
d	Installation of PV shelters provided with a charging system for electric bikes and cars	X			35,000	7,200	4.86	20.2
e	Monitoring of the energy performances of three green coverings for thermal and electric loads reduction		X	X	11,640			
f	Application to the building envelope of photocatalytic surfaces for the reduction of air pollutants			X	5,000	-	-	-
g	Replacement of transparent surfaces of buildings with innovative and transparent PV systems	X			26,600	2,067	12.87	53.4
h	Informative screens located at the entrance of the "cittadella"		X		28,000	-	-	-

12.5 Discussions and Conclusions

The adoption of the above indicated energy efficiency-related actions, leads to the modification of the CDI index, since a larger amount of the energy needs of the campus is now attributed to renewable sources of energy. The new value now attained of the CDI index is 1.092, with an improvement referring to the original value of about 2.7%. This little percentage improvement could appear as almost irrelevant in relation to the hypothesized energy efficient interventions. Anyway, it must be signalled the positive trend established by these implemented actions, whose cost is totally covered by the energy efficiency actions and tools introduced thanks to the economic savings determined by the energy policy of the University aimed at the greening of the energy consumption behaviour of its campus.

One of the most relevant parameters to be considered, in order of establishing a priority order of interventions, is certainly given by the payback time (PBT, in Table 1) of each action. It is, in fact, well evident the huge difference among the proposed actions that range from an interesting 4.4 years PBT, relative to the piezoelectric energy harvesting floor, to a problematic 53.4 years of PBT, relative to the replacement of transparent surfaces of buildings with transparent PV systems. Obviously, as far as the decision about the implementation of a given measure is in context, the leading features should not be strictly confined to economic evaluations, but should also involve consideration related to the quality of the services provided to users.

Referring to the new attained environmental profile of the campus, because of the hypothesized actions, it is worth noting that this total amount of saved energy would correspond to approximately 40 tons of avoided CO_2 emissions.

Anyway, in conclusion, it must be underlined that one of the most important characteristics of the path of the University of Palermo toward a more sustainable governance of its campus's energy-related services is the choice that the money savings, realized thanks to the energy efficiency interventions, constitute the main flywheel to finance further savings and energy efficiency actions. Interestingly, this approach could be effectively adopted by municipality institutions, for example by implementing energy saving measures in the frame of the well known ESCO (Energy Service Company) schemes.

Chapter 12 Acknowledgment

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Chapter 13 - How effective will vegetated roofs be in enhancing buildings' climate resilience in 60 years?

This chapter is based on the following recently submitted under review journal paper, which authors are Laura Cirrincione, Antonino Marvuglia and Gianluca Scaccianoce.

Abstract: In sight of enhancing urban resilience, the improvement of energy efficiency in the building sector plays a relevant role, being responsible for about 40% of both energy consumption and release of pollutants in the atmosphere. Within this context, green roofs could represent a viable solution as passive envelope components as they can have a positive impact on the indoor thermal comfort and the energy consumption, helping reducing the size of the technical plants and limiting their use. In turn, this has a positive impact on the outdoor urban environment, because it induces various benefits such as the reduction of CO_2 emissions, as well as the mitigation of the urban heat island (UHI) effect. In the research work presented in this paper, a simulation approach was used to assess how green roofs can affect the thermal behaviour of buildings, by evaluating the indoor comfort levels, the energy savings and the reduction of CO_2 emissions in two very diverse climatic settings (Esch-sur-Alzette in Luxembourg and Palermo in the south of Italy) and under different temporal and socioeconomic pathways. The outcomes of the research bring a contribution to the knowledge on the effectiveness of green roofs in the context of urban resilience to the climate change, and can provide useful information for the implementation of mitigation and adaptation plans.

Keywords: Green roofs, climate adaptation, urban sustainability, thermal building simulation, regenerative sustainability.

13.1 Introduction

Climate change has become a serious concern worldwide, with implications on health risks, social security, geopolitical stability (climate refugees), biodiversity safeguard and infrastructure protection. In the urban context, it will certainly affect more and more seriously the energy demand of buildings, further triggering sustainability concerns. Therefore, adaptation strategies supported by relevant technical solutions are of paramount importance to make cities more sustainable [Carter et al., 2015]. Cities sustainability is also one of the key Sustainable Development Goals (SDG) of United Nations (UN) [UN, 2015], with the aim of making cities more inclusive, resilient, competitive and resource efficient, and to mitigate and adapt to climate change [Marvuglia et al., 2020 (a), Bisegna et al., 2019].

New concepts, such as “regenerative sustainability” [Brown et al., 2018], have now entered in the common lexicon of the international research community [Attia, 2016, Gou & Xie, 2017, Havinga et al., 2019, Naboni et al., 2019, Plessis, 2012], with the aim of fostering approaches such as biophilia [Browning et al., 2014], salutogenesis [Golembiewski, 2012], and biomimetic architecture [Kuru et al., 2019]. One of the merits of regenerative sustainability in the building sector is the consolidation and promotion of the perception of buildings as more dynamic and interactive structures [Konstantinou et al., 2020]. Under this conceptual paradigm, a large spectrum of technical solutions for the building envelope are fostered to ameliorate occupants’ perception of indoor and outdoor space, improving not only their comfort, but their whole well-being in general. They go under the name of bio-inspired, or bio-based, or nature-based solutions, like green (or vegetated) façades, green walls and green roofs and have proven effective in mitigating the effects of extreme weather events like heat waves [Kabisch et al., 2017, Marvuglia et al., 2020 (b)] or heavy water runoffs [Koppelaar et al., in press], and phenomena like urban heat islands (UHI) [Gunawardena et al., 2017, Li & Norford, 2016, Peri et al., 2013, Razzaghmanesh et al., 2016]. They are also considered beneficial with respect to functions like air purification and consequent reduction of urban air pollution [Francis & Jensen, 2017].

In this perspective, it is of extreme importance not only being able to quantify and assess the extent to which these solutions are effective in improving climate resilience today, but also being capable of forecasting this effect, with a reasonable accuracy, under future climate scenarios. More precisely, research is needed to predict the effect of specific technical solutions that are installed in today’s highly efficient buildings, be them purely technological (such as thermally activated glass façades, phase-change material (PCM) façades, photocatalytic envelope system, etc.) or bio-based (such as cork, wood, kenaf, straw, hemp, etc.). Even further than that, the cumulative effects of these solutions when simultaneously installed on a building should be assessed, including the mutual interaction between buildings located close to each other.

This paper investigates one specific solution: vegetated roofs. The study quantifies their effects on the energy loads and the indoor comfort of the buildings where they are installed, both in today’s climate conditions and under future socioeconomic and climate scenarios (2050 and 2080 projections). In order to geographically contextualise the study, the cases of two European cities located at very different latitudes are simulated: Palermo, in southern Italy (38°06′56.37″N) and Esch-sur-Alzette, in Luxembourg (49°29'44.99" N).

13.2 State of the art on vegetated roofs

The effect of green (or vegetated) roofs on the energy demand of buildings has been studied by several authors, with a rapid increase in recent years. From the thermal point of view, the first effect of vegetated roofs consists in lowering the heat transfer to the building and consequently improving the indoor comfort conditions (in some cases up to the second to last floor).

Table 13.1 summarizes the results of the literature screening that we carried out the subject. Green roofs’ effects on heating and cooling loads have been studied in different climatic contexts and their influence on heat transfer has been simulated not only with reference to their purely vegetative characteristics (plant species, foliage coverage, evapotranspiration, etc.), but also in combination with other building components or technical solutions such as innovative roof insulation components, ventilation and windows shadings. The climate zone addressed by each reference is made explicit in Table 13.1, following the well-known Köppen-Geiger climate zones classification [Kottek et al., 2006, Peel et al., 2007, Rubel & Kottek, 2010].

Table 13.1. Main literature contributions regarding green roofs' research state of the art.

Author	Year	Location - Climate zone	Köppen-Geiger classification	Investigated parameters	Observed main results	Green roof typology	Plants species / Substrate species
Niachou et al.	2001	Loutraki region, Athens, Greece	Csa	Thermal properties (indoor and outdoor temperature measurements) and energy performance (energy savings)	2°C indoor temperature improvement; total energy savings: 37-48% (no-insulation), 4-7% (moderate insulation), 2% (good insulation)	Different U-values: non-insulated, with moderate insulation, well insulated	-
Teemusk & Mander	2009	Estonia	Dfb	Temperature fluctuations (thermal insulation), temperature regime on the green roof's surface and in the green roof's substrate layer	Reduction of the overheating of air in cities (protection against intensive solar radiation): the air temperature fluctuated by 8.3°C on average	LWA[1] extensive	Sedum acre (55%), Thymus serpyllum (20%), Dianthus carthusianorum (5%), Cerastium tomentosum (3%) Veronica filiformis (7%)
Sailor & Hagos	2011	Western US	Dfa, Dfb, Cfa, Cfb	Thermal conductivity	The conductivity values range from 0.12 to 0.74 W/(mK)	12 samples of 3 soil aggregates containing different % of porous silica, expanded slate, expanded clay, compost, sand	
Jaffal et al.	2012	Temperate oceanic climate (La Rochelle - France)	Cfb	Heat flux through the roof (W/m^2), indoor air temperature and cooling and heating demand (kWh/m^2 year)	The summer indoor air temperature was decreased by 2°C and the annual energy demand was reduced by 6%	Irrigated extensive	Sedum with soil composed of a mixture of 40% organic materials (compost) and 60% volcanic materials (pozzolan)
Peri et al.	2012 (a)	Mediterranean climate (Sicily)	Csa	Environmental performance (green roof substrate LCA[2])	The substrate resulted to be the largest contributor to the Acidification, Eutrophication and Fresh Water Aquatic Ecotoxicity potential	Extensive	Halimonie Portulacoides, Rosmarinus officinalis, Crithum Maritimum / Agriterram©TVS, Igroperlite©T1, Ecodren©SD5, Soiphren©H
Peri et al.	2012 (b)	Mediterranean climate (Sicily)	Csa	Environmental performance (green roof disposal LCC[3] and LCA)	The obtained results clearly highlight the importance of including the end of life and especially the growing medium disposal	Extensive	Halimonie Portulacoides, Rosmarinus officinalis, Crithum Maritimum / Agriterram©TVS, Igroperlite©T1, Ecodren©SD5, Soiphren©H
Peri et al.	2013	*review article*	-	UHI effect mitigation relative to the canopy	-	-	-

				(comparison between different models)			
Saadatian et al.	2013	*review article*	-	A review of energy aspects (temperature, heat flux, solar radiation, acoustic performance, UHI[4], cooling load)	-	-	-
Berardi et al.	2014	*review article*	-	State-of-the-art of the environmental benefits	-	-	-
Goussous et al.	2014	Jordan		Thermal benefits (thermal transmittance, solar gains) and energy saving % (energy consumption of HVAC[5] systems, heating and cooling Wh)	41% thermal efficiency increase and heat loss decrease; 17% total energy saving in the building	Intensive	Grass, Sedum
Zhao et al.	2014	Different climate zones in the US: Austin, Sacramento, Nashville, Chicago.	Cfa, Csa, Cfa, Dfa	Roof surface energy balance: substrate heat fluxes and net radiation fluxes	Plant species showed an average difference of 16% in the peak net radiation and 20% in the average net radiation (due to spectral reflectivity)	Extensive	Sedum spurium, Sedum hispanicum, Sedum rupestre Angelina, Sedum sexangulare, Sedum tomentosum / Norlite, Perlite, “Cellar market”, Rooflite media
Bozorg Chenani et al.	2015	Finland	Dfc, Dfb,	Environmental impacts of the layers used in the construction of green roofs (LCA)	Water retention, drainage and substrate layers are the components characterized by the greatest negative environmental impact	LWA	-
Pisello et al.	2015	Perugia, Italy	Cfb	Thermal-physical solar reflectance and thermal emittance, indoor overheating hours, PMV[6], PPD[7] and primary energy requirement for cooling	98.2% reduction in the number of indoor overheating hours and 3°C decrease in the indoor operative temperature during summer; decrease in primary energy demand of up to 97% for cooling and up to 42% for heating	Extensive Cool-Green Roof	Helichrysum Italicum “Curry plant”

				and heating (kWh)			
Yang et al.	2015	Sub-tropical climatic region: Guangzhou (China)	Cfa	Thermal performance: indoor air temperature (°C) and air conditioning power consumption (kWh/d m^2)	0.95°C indoor air temperature reduction (in average), 15.2% air conditioning power reduction	Extensive	Sedum lineare
Buckland-Nicks et al.	2016	Cold, humid, maritime climate (Halifax - Canada)	Dfb	Thermal performance (indicated by heat flux and substrate temperature)	Substrate temperature (°C) average: winter mean 0.65±0.06, summer mean 19.21±0.1; Heat Flux (W/m^2)^2 average: winter mean -4.26±0.06, summer mean -0.65±0.03	Extensive	Sibbaldiopsis tridentata, Solidago bicolor
Coma et al.	2016	Mediterranean continental climate conditions (Spain)	Csa	Thermal behaviour (internal ceiling temperature) and sustainability (cumulative electricity consumed, kWh)	Energy consumption: -2.2% ÷ -16.7% during warm periods, +6.1% ÷ +11.1% during heating periods; internal ceiling temperature fluctuation ±1°C	Extensive	Deslosperma and Sedum
Ferrante et al.	2016 (a)	Mediterranean climate (Sicily)	Csa	Energy consumption savings (kWh) relative to different plant species	Cooling energy savings comprised between 8% and 20%	Extensive	Phyla nordiflora, Aptenia lancifolia, Mesembryanthenum barbatus, Gazania nivea, Gazania uniflora and Sedum
Gargari et al.	2016	Mediterranean hot climate (Pisa)	Csa	Overall impact of the green roofs (LCA)	Lack in specific life cycle inventory information regarding recycled material (used in the growing medium) and disposal scenarios	Extensive and intensive	Sedum and grass
Peri et al.	2016	Mediterranean climate (Sicily)	Csa	Thermal behaviour: differences between the canopy shortwave solar radiation exchanges literature models	The error potentially occurring in the annual energy need (cooling and heating) estimation is ranged between approximately 2% and 17%	Extensive	Phyla nordiflora, Aptenia lancifolia, Mesembryanthenum barbatus, Gazania nivea, Gazania uniflora
Razzaghmanesh et al.	2016	Adelaide, Australia	Csb	UHI effect mitigation (surrounding micro-climate temperature	Green roofs can be 2 to 5◦C cooler during the day and 3 to 6◦C warmer during the night with	Extensive and intensive	-

				monitoring)	respect to the ambient air temperatures.		
X.-X. Li & L.K. Norford	2016	Singapore	Af	UHI mitigation effect of the cool roof and green vegetations at the city scale (near-surface air temperature and surface skin temperature)	Green vegetation can reduce the near-surface air temperature by 1 to 2°C during night-time when the UHI intensity is high and, moreover, it will improve human’s physiological thermal comfort during early morning	Extensive	Grass
Francis & Jensen	2017	*review article*	-	Reduction of the UHI effect, reduction of urban air pollution, and reduction of building energy consumption	-	-	-
Koura et al.	2017	Mediterranean climate (Lebanon)	Csb, Csa	Temperature profile for different substrate depths (heat storage effect during cold seasons and passive cooling effect during hot seasons)	Air temperature fluctuations were mitigated throughout the 4 seasons: during winter by 4.7and 5.7°C, during fall by 5.7 and 5.8°C, during spring by 5.9 and 6.4°C, and during summer by 7.4 and 7.2°C	Extensive	Rosemary, Lavender, Alyssum, Argyanthemum madeira, Marguerite daisy, Gazania rigens, Lobularia maritima
Vaz Monteiro et al.	2017	Reading, UK	Cfb	Summertime environmental cooling and substrate insulation potential	Results suggest that, amongst the considered species, Salvia and Stachys may have an important role to play in cooling the surrounding environment and improving the daytime thermal insulation of buildings in the summer	Extensive	Heuchera ‘Obsidian’, Heuchera ‘Electra’, Salvia officinalis ‘Berggarten’, Stachys byzantina, Sempervivum ‘Reinhard’, Sedum mix
Vera et al.	2017	Semiarid (Albuquerque - USA, Santiago - Chile) and marine (Melbourne - Australia)	BSk, Csb, Cfb	Thermal (heat fluxes, W/m^2) and energy performance (heating and cooling loads, kWh/m^2 year)	Vegetation can effectiveness on reducing cooling loads is due more to evapotranspiration and canopy’s shading effects than to LAI[8]	Extensive	Sedum spurium (Dragon’s Blood), Sedum hispanicum, Sedum rupestre Angelina, Sedum sexangulare, Sedum tomentosum, mixed Sedum, S. spurium

Yeom & La Roche	2017	Hot and dry, southern California	Csb	Thermal comfort (indoor temperatures) and energy consumption (cooling potential)	Lower indoor temperatures 5.33◦C on the average (St. Dev:0.96)	Green roof paired with a radiant cooling system	Succulents appropriate to the climate with a LAI of 4.
Zeng et al.	2017	Four climate zones in China: Harbin, Beijing, Chongqing, and Guangzhou	Dwa, Dwa, Cfa, Cfa	Energy savings rates, % (heating and cooling energy consumptions, kWh/m^2 year) and indoor thermal comfort, hours exceeding three reference operative temperatures	In terms of energy savings, the recommended soil thickness and leaf area index in the four cities are 0.3 m and 0.5, respectively. The optimal plant height is 0.3 m, except in Beijing, where it is 0.1 m.	-	-
Ran & Tang	2018	Hot and humid climate (Shanghai)	Cfa	Effect of green roof, night-time ventilation ad walls insulation combination on indoor average temperature	The indoor average temperature can be reduced by up to 2.3 °C	Extensive	Sedum lineare
Cao J., Hu S. and Dong Q. et al.	2019	Shanghai, China	Cfa	Different plant species green roof cooling effects (canopy temperatures)	C4 performed a superior canopy cooling (16.3 ÷ 16.9°C) than C3 (12.6 ÷ 14.7°C) and CAM performed the lowest (5.4 ÷ 8.6°C); all green roofs performed significant cooling in soil profile; significant night cooling was noticed only in CAM	Extensive	C3 (Poa pratensis and Festuca arundinacea); C4 (Cynodon dactylon and Eremochloa ophiuroides); CAM (Sedum lineare and Callisia repens)
Susca	2019	*review article - different climates comparison*	-	Geographically explicit review of the potential building energy benefits, heating and cooling variation in energy demand (%) and UHI mitigation (T)	-	-	-
Bevilacqua et al.	2020	Mediterranean climate (Calabria)	Csa	Cooling energy demand (kWh) and indoor thermal comfort	Annual savings of 34.9% in continuous operation and of 34.7% in intermittent operation.	Extensive	Dianthus grantianopolitanus, Carpobrotus edulis and Cerastium tomentosum

				(discomfort degree hours)	Reduction of the discomfort degree hours comprised between 7% ÷ 80% based on the configuration.		
Cirrincione et al.	2020 (a)	Mediterranean climate (Sicily)	Csa	Indoor comfort (Tceiling and PMV), energy consumption (kWh), and CO_2 reduction	2°C average ceiling temperature mitigation; 0.2 average PMV reduction; mean indirect and direct CO2 emissions reduction of 145.6±13.8 tCO2/year and 56 gCO2/year respectively; 23% average annual energy consumptions reduction for heating and cooling needs	Extensive	Halimione Portulacoides, Rosmarinus Officinalis Prostratus and Crithmum Maritimum
Koura et al.	2020	Al Kurah, North Lebanon	Csa	Cradle-to-grave life cycle environmental impacts	The environmental impacts of EGR are lower than the ones of TGBRs[10] approximately all the impact categor (except for “carcinogens” and “wat scarcity”). Furthermore, installation EGRs on wide surface areas reduce the yearly residential electricity consumption of 48.15% by decreasi the need for a heating/cooling syste	Extensive	Rosemary, Lavender, Alyssum, Argyanthemum madeira, Marguerite daisy, Gazania rigens, Lobularia maritima
Cirrincione et al.	2020 (b)	65 Italian sites	Csa, Cfa, Cfb	Comparing energy efficiency and indoor performances	The actions for improving heating and cooling energy savings sometimes lead to a reduction of indoor comfort (PMV and PPD).	Four different roof configurations	
Cirrincione et al.	2020 (c)	Mediterranean climate (Sicily)	Csa	Overall energy-environmental impact (LCA)	Except for the abiotic depletion (ADP) and the terrestrial ecotoxicity (TEP), the phase which weighs more on the LCA is the production one (water storage, drainage, substrate and filter elements).	Extensive	Phyla nordiflora, Aptenia lancifolia, Mesembryanthenum barbatus, Gazania nivea, Gazania uniflora
Fabbri et al.	2020	Mediterranean	Csa	Hygrothermal behavior of coconut fiber insulators on green roofs	Results on transmittance U (W/m^2K) show that coconut fiber insulations are equally comparable to natural and synthetic materials.	-	-

Andric et al.	2020	Doha, Qatar	BWh	Specific annual energy consumption (kWh/m2/yr), indoor temperature	Across future temperature scenarios until 2080, a green roof and green wall allowed 3% annual savings in building energy consumption; much less than envelope renovation (addition of 5-cm expanded polystyrene and the installation of energy-efficient windows), which allowed a reduction up to 30%.	Extensive	Not specified, but plant properties (Height, LAI, Leaf reflectivity, Leaf emissivity, Minimum stomatal resistance, Max. volumetric moisture content at saturation, Min. residual volumetric moisture content) assigned
Mohapatra S., Verma S., Chowdhury S. et al.	2020	*review article*	-	Thermal insulation, effects of shading and cooling, heat flux and evapotranspiration, reduction of carbon emissions, water savings and, microclimatic conditions. LCA and its limitations.	The heat flow in buildings can be reduced by 74%. Green roofs also aide in keeping the building warm during winters while retaining rainwater during the rainfall season.	various components and types of green roofs	
Cirrincione & Peri	2021	Mediterranean climate (Sicily)	Csa	*review book chapter*	A review of energy aspects, environmental performance and economic considerations	Extensive	Different species and substrate compositions

[1]LWA= Light Weight Aggregates; [2]LCA=Life Cycle Assessment; [3]LCC= Life Cycle Costing; [4]UHI= Urban Heat Island; [5]HVAC= Heating, Ventilation and Air Conditioning; [6]PMV= Predicted Mean Vote; [7]PPD= Predicted Percentage of Dissatisfied; [8]LAI= Leaf Area Index; [9]EGRs= Extensive Green Roofs; [10]TGBRs= Traditional Gravel Ballasted Roofs

13.3 Materials and Methods

As mentioned above, this study takes a simulation-based approach. Figure 13.1 shows a flowchart of the work carried out in this paper, where the thermal building simulations and their outcomes are framed by tick red boxes.

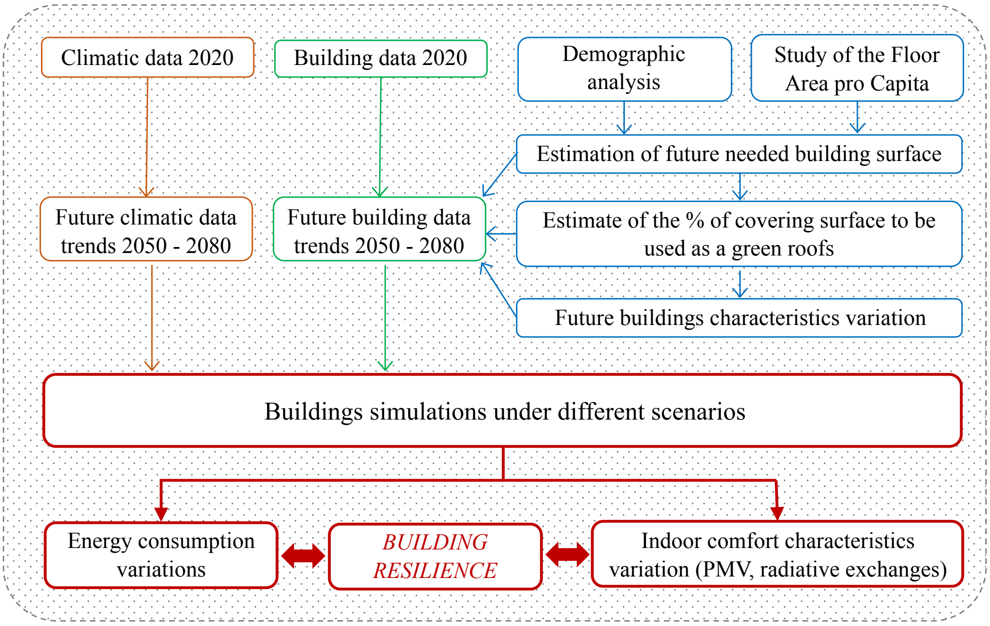


Figure 13.1. Block diagram of the logical process of the work presented in the paper.

The following sections will describe more in detail each step of the block diagram.

13.3.1 Climatic description of the two investigated sites

Concerning the climate characteristics of the two studied cities, Esch-sur-Alzette belongs to the West European Continental climatic region, characterized by a temperate climate with mild-to-cold winters, cool summers (with a mean annual temperature of 10 °C) and high-rate rainfall (about 800-1200 mm in a year), which results in overcast skies and considerable drizzle, especially during winter; while the sunniest period is the one comprised between the months of May and August [https://gouvernement.lu/en.html, https://www.visitluxembourg.com/en].

Palermo is one of the sunniest and warmest cities in Europe (with a mean annual temperature of 18 °C). Its weather conditions are typical of a subtropical Mediterranean climate, characterized by a moderate seasonality with long hot dry summers (although frequently windy thanks to the presence of sea breezes) and mild changeable winters (with low-rate rainfall due to the polar front), temperatures in autumn and spring are also typically warm [www.palermo.climatemps.com].

Table 13.2 summarizes the main weather parameters for the selected cities in order to better highlight the difference between the two sites according to the well-known Köppen-Geiger classification [Kottek et al., 2006, Peel et al., 2007, Rubel & Kottek, 2010] and also point out the diverse climate characteristics during the heating and cooling seasons. These latter have been extrapolated from the weather database of the EnergyPlus simulation code [https://energyplus.net], which was used in this work to run simulations.

Table 13.2. Main weather parameters for the two selected cities.

	Esch-sur-Alzette (Luxembourg)	**Palermo (Italy)**
Latitude	49°29′49″ N	38°06′56.37″ N
Longitude	5°58′49″ E	13°21′40.54″ E
Altitude in meter (a.s.l.)	352	14
Köppen-Geiger climate class	Cfb	Csa
Heating Degree Days (HDD) [a]	2773	1000
Cooling Degree Days (CDD) [b]	11	73
Cumulate solar radiation for heating season (MWh)	281	526
Cumulate solar radiation for cooling season (MWh) [b]	808	1156

[a] Considering heating season period 15th October – 14th April.

[b] Considering cooling season period 15th April – 14th October.

13.3.2 Climate analysis and weather scenarios trends (2020, 2050, 2080)

As mentioned above, the weather data used for simulation have been acquired from the EnergyPlus website database [https://energyplus.net/weather]. However, while the data for Palermo were actually available, data associated to Esch-sur-Alzette were missing from this database. Therefore, it was decided to consider those relative to the nearby (around 92 km far) French town of Nancy (coordinates: 48°40′48″ N, 6°13′12″ E; average altitude: 217 m a.s.l.) since it was the closest to Esch-sur-Alzette also in terms of weather conditions. This choice appears to be reasonable, considering that the temperature trends in the two cities are very similar. To confirm such assumption, the root mean square error (RMSE) among the temperatures of Nancy [https://www.wunderground.com] and Esch-sur-Alzette [https://www.meteolux.lu], was also calculated for a range of data going from January 1st 2020 to December 31st 2020, and resulted in a low value (1.2 °C), as showed in Figure 13.2.

Finally, the data utilized to build the future trends weather conditions refer to the years 1989 and 1983 for Nancy and Palermo, respectively.

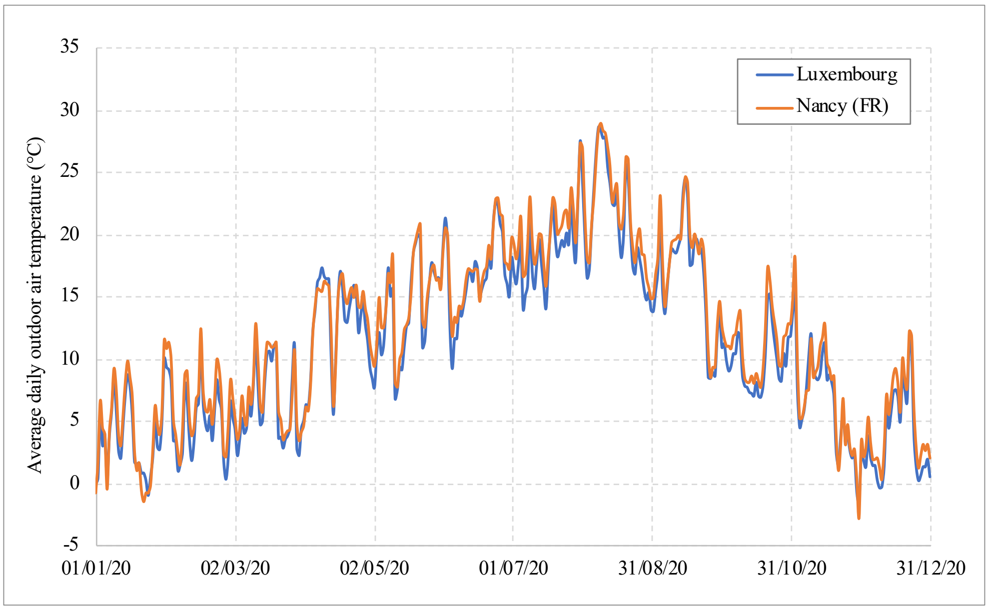


Figure 13.2. Difference between the daily average outdoor temperatures of the two considered sites.

In order to build the weather files related to the three considered future years, 2020 - 2050 - 2080, the Climate Change World Weather Generation (CCWorldWeatherGen) tool has been used [University of Southampton, 2020]. This tool allows to obtain a future hourly weather file starting from a current one using the IPCC TAR model summary data of the HadCM3 A2 experiment ensemble (HRM3). In particular, the tool was built using the time series adjustment (morphing) technique as statistical downscaling method to develop a future weather file based on an existing .epw file [Jentsch et al., 2013, Belcher et al., 2005, Berardi & Jafarpur, 2020]. In fact, building simulation models (such as EnergyPlus) need hourly data as input while Global Climate Models (GCMs) provide only large spatial scale monthly data, which hence need to be temporally and spatially downscaled.

The weather file for the year 2020 was also generated using this tool, in order to have an equal refence point, since the .epw files related to the climatic data of the two considered sites refer to different origin years.

Figure 13.3 and Figure 13.4 show the annual trend of outdoor air temperature and solar radiation for the year 2020 for Nancy and Palermo, obtained from the data contained into the .epw files generated by CCWorldWeatherGen tool.

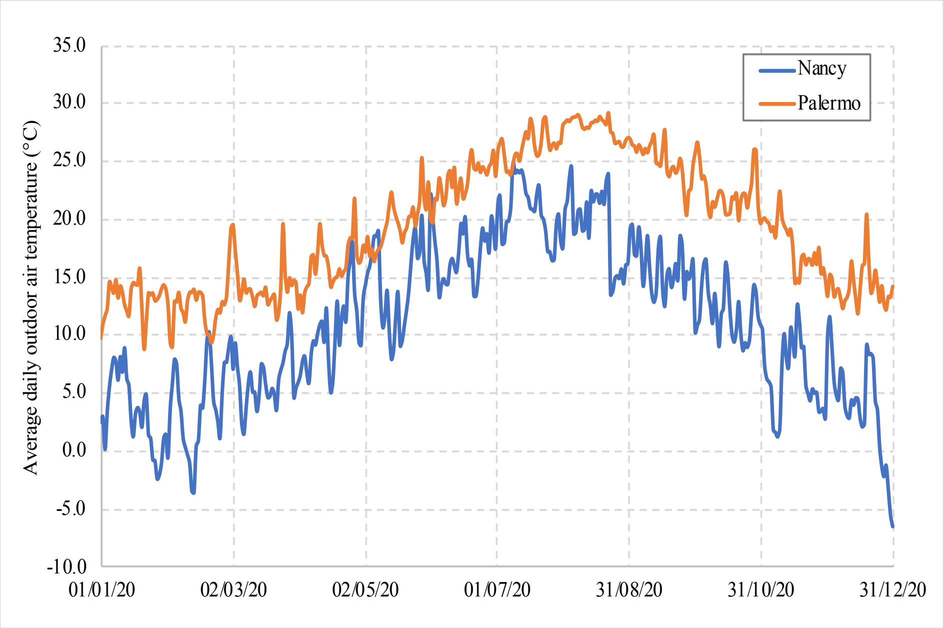


Figure 13.3. Trends of outdoor air temperature for Nancy and Palermo, for the year 2020.

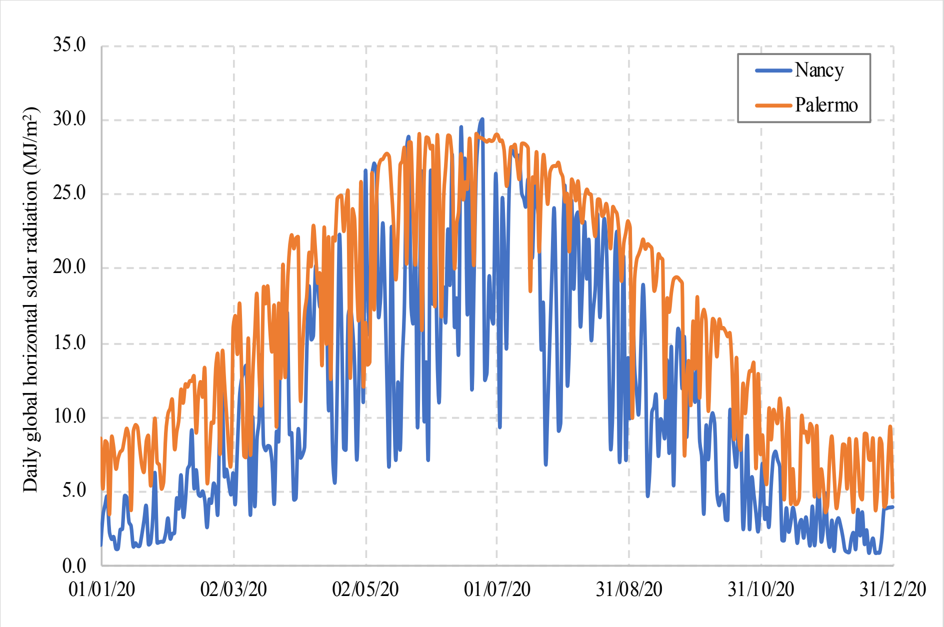


Figure 13.4. Trend of annual solar radiation for Nancy and Palermo, for the year 2020.

Moreover, with the aim of evaluating the ability of HRM3 to accurately reconstruct the climate data, the daily dry bulb output values for the period of January-December 2020 were compared with the actual data monitored from the weather stations in the same period. It was thus possible to obtain the relative RMSE values, which resulted being equal to 2.5 and 4.5 for Palermo and Nancy, respectively, in accordance with values found in literature [Berardi & Jafarpur, 2020].

13.3.3 Analysis of the evolution of built surfaces: 2020-2050-2080 trend

The evolution of the built surface for the future scenarios in the two studied areas has been estimated taking as a reference the current building and demographic data [https://statistiques.public.lu/, Eurostat, ISTAT, IIASA], which were analysed and combined with the information related to the floor area pro capita [Riahi et al., 2017, Vásquez et al., 2016] in order to calculate the future needed building floor surface, the building footprint areas and, hence, estimate the future available area for the green roofs. These aspects will be better detailed in Sections 13.3.3.1 and 13.3.3.2.

Regarding the future scenarios, it was decided to refer to the Shared-Socioeconomic Pathways (SSPs) assumptions, introduced in [Bauer et al., 2017, O'Neill et al., 2017] with the aim of contributing to future research in the area of environmental sustainability and climate change. The rationale behind the SSPs is that the socioeconomic conditions and drivers which have a significant impact on the energy system and its future growth (such as demographics, economy, lifestyle, policies, institutions, technology and environment and natural resources) can be structured into five alternative development pathways narratives, at the level of large world regions, arranged so as to investigate climate impacts as well as options for mitigation and adaptation. Specifically, the five SSPs are:

- SSP1 *"Sustainability—Taking the green road"*, low challenges to both mitigation and adaptation;
- SSP2 *"Middle of the road",* moderate challenges to mitigation and adaptation;
- SSP3 *"Regional rivalry—A rocky road"*, high challenges to either mitigation and adaptation;
- SSP4 *"Inequality—A road divided"*, low challenges to mitigation and high challenges to adaptation;
- SSP5 *"Fossil-fueled development—Taking the highway"*, high challenges to mitigation and low challenges to adaptation.

13.3.3.1 Study of the demographic trend

The study of the demographic trend has been carried out taking as a reference the data on the population evolution related to a 2010-2020-time window [https://statistiques.public.lu/, Eurostat, ISTAT].

Concerning the period spanning from 2030 to 2080, starting from the comparison between the local (Esch-sur-Alzette and Palermo) and national (Luxembourg and Italy) population percentages for the years 2010-2020, a linear regression was applied, from which the city populations for the following years were subsequently obtained. Afterwards, these values were multiplied by the population estimates provided for the respective countries by the future demographic forecasts of the International Institute for Applied Systems Analysis – IIASA [IIASA] and also considering the previously described SSPs [Riahi et al., 2017]

Figure 13.5 and Figure 13.6 show the resulting projections of demographic trend previsions on national and local basis, respectively.

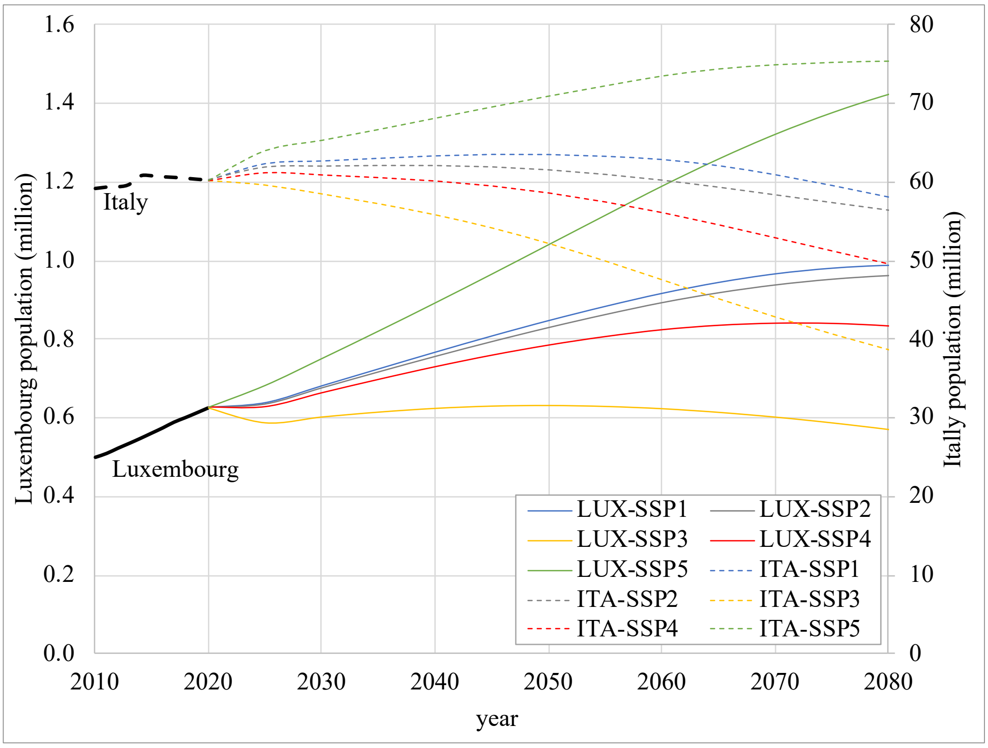


Figure 13.5. National demographic trends for Luxembourg and Italy, in the five SSPs.

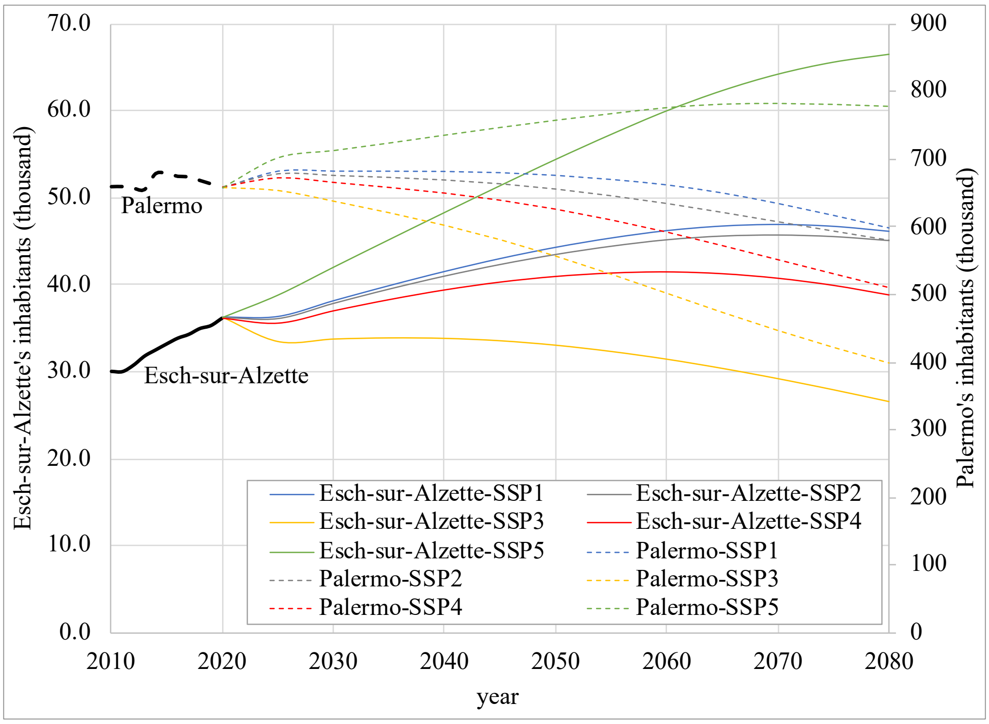


Figure 13.6. Demographic trends for Esch-sur-Alzette and Palermo, in the five SSPs.

It should be here pointed out that, being Palermo a large city, from the reference data [https://statistiques.public.lu/, Eurostat, ISTAT] and taking into account the existing space constraints and the limits (in terms of allowed building areas) imposed by the city building master plan and the redevelopment policies concerning Palermo's southern waterfront zone [https://www.comune.palermo.it/territorio.php], it was deduced that the "Bandita" district considered in this study is one of the most likely to host the future increase in the number of buildings due to the demographic growth.

13.3.3.2 Development of built surfaces

Starting from the results of the demographic trend analysis, the current built-up areas data [Mastrucci et al., 2017, Peri et al., 2017, Ferrante et al., 2016 (b), Filogamo et al., 2014], and the forecasts of future net floor area per person (*FApC*) [Vásquez et al., 2016, EU, 2011], it was possible to estimate the future building net footprint area (A_{net}) necessary to accommodate the future population, for the two future time scenarios considered, i.e. 2050 and 2080.

More specifically, for both sites and for all the SSPs, the difference between the expected and the current population was first calculated. The result was then multiplied by a *FApC* value of 45 m^2, thus obtaining the total building surface (S_{tot}) required in the future to meet the demographic growth. The variation in the number of future buildings in terms of gross footprint area (A_{gross}) was calculated by, firstly dividing S_{tot} for 180 m^2, representing the surface of two European standard apartments (90 m^2 each) [Vásquez et al., 2016], and secondly by dividing by such value for the number of floors, thus obtaining the number of standard dwellings having two apartments per floor. To this purpose, it was decided to consider 6 and 5 floors as representative values for Esch-sur-Alzette and Palermo, respectively, since they correspond to the most recent constructed typology of buildings (see Table 13.5 and Table 13.6 in Section 14.3.4). Finally, to take into account the space occupied by cornices, technical systems and ancillary services to the green roofs, A_{net} was estimated considering reduction factors of 12% for Palermo [UNI, 2014 (a)], and 20% for Esch-sur-Alzette [Mastrucci et al., 2017].

Table 13.3 and Table 13.4 summarize the results of the procedure described above applied to Esch-sur-Alzette and Palermo's Bandita district for each of the five SSP and of the three years 2020, 2050 and 2080.

Table 13.3. Demographic trend results.

	Expected population (thousands of people)			**Expected population variation (thousands of people)**	
	2020	2050	2080	2050-2020	2080-2020
Esch-sur-Alzette-SSP1	36.22	44.30	46.15	8.08	9.93
Esch-sur-Alzette-SSP2	36.22	43.41	45.00	7.19	8.78
Esch-sur-Alzette-SSP3	36.22	33.05	26.64	-3.17	-9.58
Esch-sur-Alzette-SSP4	36.22	40.99	38.88	4.77	2.66
Esch-sur-Alzette-SSP5	36.22	54.42	66.51	18.20	30.29
PA-Bandita-District-SSP1	49.48	50.89	44.98	1.42	-4.50
PA-Bandita-District-SSP2	49.48	49.26	43.64	-0.22	-5.84
PA-Bandita-District-SSP3	49.48	41.84	29.93	-7.64	-19.55
PA-Bandita-District-SSP4	49.48	47.02	38.38	-2.46	-11.10
PA-Bandita-District-SSP5	49.48	56.90	58.43	7.42	8.95

Table 13.4. Development of total built surfaces results.

	Expected number of standard dwellings		**A_{gross} (m^2)**		**A_{net} (m^2)**	
	2050	2080	2050	2080	2050	2080
Esch-sur-Alzette-SSP1	168.29	206.89	3.64E+05	4.47E+05	2.91E+05	3.58E+05
Esch-sur-Alzette-SSP2	149.81	182.89	3.24E+05	3.95E+05	2.59E+05	3.16E+05
Esch-sur-Alzette-SSP3	-66.02	-199.61	-1.43E+05	-4.31E+05	-1.14E+05	-3.45E+05
Esch-sur-Alzette-SSP4	99.35	55.52	2.15E+05	1.20E+05	1.72E+05	9.59E+04
Esch-sur-Alzette-SSP5	379.12	631.05	8.19E+05	1.36E+06	6.55E+05	1.09E+06
PA-Bandita-District-SSP1	470.65	-1494.53	8.47E+05	-2.69E+06	7.46E+05	-2.37E+06
PA-Bandita-District-SSP2	-72.87	-1941.39	-1.31E+05	-3.49E+06	-1.15E+05	-3.08E+06
PA-Bandita-District-SSP3	-2540.27	-6500.03	-4.57E+06	-1.17E+07	-4.02E+06	-1.03E+07
PA-Bandita-District-SSP4	-818.84	-3690.48	-1.47E+06	-6.64E+06	-1.30E+06	-5.85E+06
PA-Bandita-District-SSP5	2467.43	2976.78	4.44E+06	5.36E+06	3.91E+06	4.72E+06

As it can be noticed, while Esch-sur-Alzette shows a positive trend for all the SSPs except SSP3, the same cannot be observed for the Bandita district of Palermo, where only SSP5 and SSP1 at 2050 show an increase (predicted negative trends are reported in grey).

13.3.4 Buildings selection and characteristics

With the aim of implementing simulations that would best reflect reality, given the high variety of building types present in both considered territories, a selection needed to be done in order to find those most representative for each considered site.

To this aim, data related to the buildings' geometry and materials, and the layout of the studied city areas, were retrieved from previous projects and monitoring campaigns realised by the authors in the respective areas [Mastrucci et al., 2017, Peri et al., 2017, Ferrante et al., 2016 (b), Filogamo et al., 2014].

The collected data were then analysed in order to first categorize the buildings, based on the construction period, the roof typology (only flat roofs were considered), the kind of materials utilized for both the opaque and glazed surfaces and the installed technical plants.

Afterwards, based on the aforementioned categorization, for each town, it was decided to select two representative type buildings for every construction period to assess the diverse impact that green roofs may have on the distinct building configurations.

Table 13.5 and Table 13.6 report the main geometrical characteristic of the selected buildings for Esch-sur-Alzette and Palermo, respectively.

Table 13.5. Geometrical characteristics for the selected buildings in Esch-sur-Alzette.

Construction period	Building ID	Total number of floors	Foot area (m^2)	Total heated/cooled surface (m^2)	Main façade orientation
< 1949	LU_Esch_I_01	3	178	535	NE
	LU_Esch_I_02	3	112	335	NW
1950-1968	LU_Esch_II_03	3	167	501	NW
	LU_Esch_II_04	3	168	503	NW
1969-1994	LU_Esch_III_05	5	128	641	NE
	LU_Esch_III_06	5	276	1382	NE
> 1995	LU_Esch_IV_07	3	78	233	NW
	LU_Esch_IV_08	6	488	2929	NE

Table 13.6. Geometrical characteristics for the selected buildings in Palermo.

Construction period	Building ID	Total number of floors	Foot area (m^2)	Total heated/cooled surface (m^2)	Main façade orientation
< 1945	IT_PA_I_01	4	117	468	NW
	IT_PA_I_02	2	49	98	NW
1946-1971	IT_PA_II_03	5	649	3245	NE
	IT_PA_II_04	4	81	324	NW
1972-1991	IT_PA_III_05	8	279	2232	NW
	IT_PA_III_06	10	984	9840	NE
> 1991	IT_PA_III_07	3	216	648	N
	IT_PA_IV_08	5	475	2375	NW

Table 13.A.1.a, Table 13.A.1.b., Table 13.A.2 and Table 13.A.3 reported in Supporting Information (SI) in Chapter 13 Appendices summarize the construction features of interest for the selected buildings of the two towns, where the materials of the specific building elements have been classified according to the UNI TR 11552 standard [UNI, 2014 (b)].

Figure 13.7 and Figure 13.8 show the layout of the selected buildings in the city of Esch-sur-Alzette and in the considered district (Bandita) of the city of Palermo, respectively.

Figure 13.7. Layout of the selected buildings in the city of Esch-sur-Alzette.

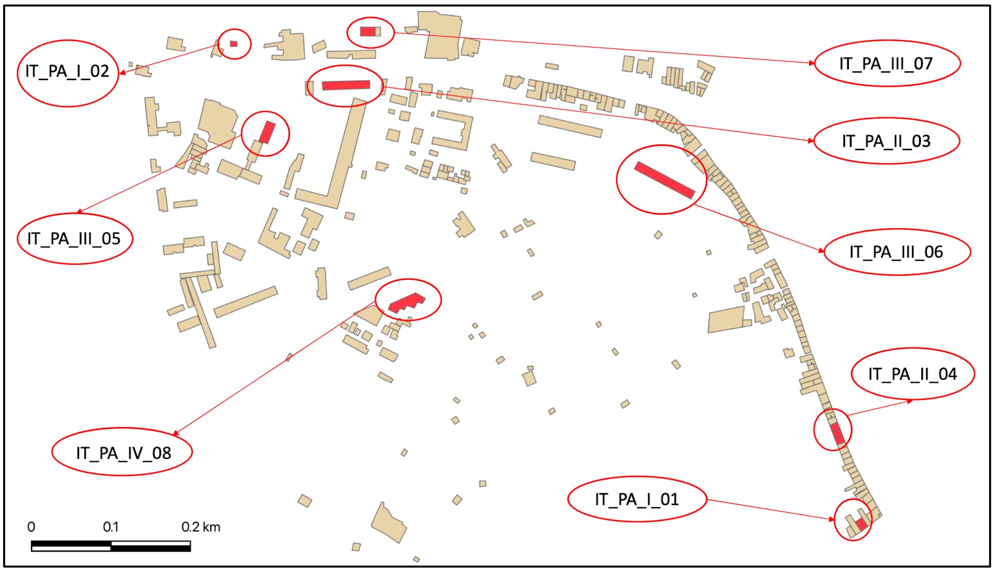


Figure 13.8. Layout of the selected buildings in the district Bandita of the city of Palermo.

13.3.5 Simulation model implementation

The building's thermal simulations were carried out using the EnergyPlus simulation software [https://energyplus.net]. Specifically, the software was used to evaluate the indoor comfort levels, by means of the predicted mean vote (PMV) index [Fanger, 1970], and the energy demand (kWh) of the considered buildings. For this purpose, for each SSPs two different scenarios were implemented. More specifically:

- Scenario #1, in which the simulation was conducted by implementing a standard case (ST), that is, considering the original roof of the building without the presence of green coverage.

- Scenario #2, in which the simulation was carried out utilizing the green roof configuration provided by EnergyPlus (GR), by substituting the outside layer of the roof with a green roof characterized by the following parameters:
    - water storage layer thickness (cm): 10;
    - height of plants canopy (m): 0.30;
    - leaf area index “LAI” (-): 3.8;
    - leaf reflectivity (-): 0.21;
    - substrate total thickness (m): 0.25;
    - thermal conductivity of dry soil ($W \cdot m^{-1} \cdot K^{-1}$): 0.0816;
    - density of dry soil ($kg \cdot m^{-3}$): 446;
    - specific heat of dry soil ($J \cdot kg^{-1} \cdot K^{-1}$): 1060.

In both the scenarios, the schedule for an ideal HVAC system was implemented (see Supporting Information), characterized by 21°C and 25°C as heating and cooling setpoints’ temperatures, respectively. These average values were obtained from simulations previously conducted using the climatic design-days typical of winter and summer conditions for the two investigated areas.

In addition, an estimation of the CO_2 emissions’ reduction has also been performed, considering for the cooling energy demand the emission factors for electricity shown in Table 13.8.

These values have been derived starting from the electricity mixes given by [Vandepaer et al., 2019] until 2050 and using the shares of each electricity source in the mix calculated from [Vandepaer et al., 2019] and the GWP100 emission factors calculated from Ecoinvent v3.5 with the ILCD 2016 impact assessment method.

In the case of Esch-sur-Alzette, an additional step has been performed, because the electricity mix in Luxembourg is heavily dependent from the electricity imported from the neighbouring countries (France, Belgium and Germany). Therefore, firstly the shares of electricity imported from each of these three countries, as well as the national electricity production for Luxembourg, obtained from [ILR, 2019] from 2015 to 2019, were linearly interpolated to obtain the shares until 2050 (see Table 13.7). Then, the shares of electricity imported from each of the three countries were used to calculate a weighted average of the emission factors for the electricity in Luxembourg. The values of the emission factors for 2080 were instead simply obtained assuming a maximum improvement of 10% with respect to the values for 2030. All the values of the emission factors are showed in Table 13.8. They take into account the emissions due to transmission losses (i.e. those occurring between the “electricity supplied” and “electricity consumed” steps in [Moro et al., 2018]). These additional emissions have been calculated from Table 2 of [Moro et al., 2018, pag. 9], resulting in about 7.2% for Italy and about 1.5% for Luxembourg.

Table 13.7. Shares of electricity imported by Luxembourg (LU) from the neighbouring countries (BR, FR, DE) and produced in the national territory.

Year	Import from BE (%)	Import from FR (%)	Import from DE (%)	LU own production (%)
2020	5.4	19.5	61.7	13.4
2030	5.7	29.5	47.7	17.1
2040	6.0	39.5	33.7	20.8
2050	6.3	49.4	19.7	24.5

Table 13.8. Emission factors for electricity ($kgCO_{2eq}\cdot kWh^{-1}$) used for Palermo and Esch-sur-Alzette.

Year	Palermo	Esch-sur-Alzette
2020	0.48	0.43
2050	0.20	0.19
2080	0.18	0.17

For the heating needs a thermal emission factor equal to 0.275 $kgCO_{2eq}\cdot kWh^{-1}$ (corresponding to 0.076 $kgCO_{2eq}\cdot MJ^{-1}$) [Vandepaer et al., 2019] has been considered. Such values are based on energy saving for climatization purposes (setting Coefficients of Performance – COPs – equal to 3 and 0.9 for cooling and heating seasons respectively).

13.4 Results and Discussion

13.4.1 Application of the simulation model to the single building

This section shows the application of the simulation model at the single building level, considering the climatic data of the three years 2020, 2050 and 2080, to estimate the time trend related to the effectiveness of green roofs in the two investigated geographical contexts.

Since the main aim of this work was to assess how the use of green roofs can affect the indoor comfort and the energy consumption of a building, it was decided to show a comparison between standard roofs (ST) and green roofs (GR) by reporting the simulation results relative to the PMV values (Figure 13.9), the ceiling temperatures and the heating and cooling energy savings (Figure 13.10).

It should be here underlined the fact that for both the considered geographical contexts the behaviour of the buildings belonging to the same categories resulted being very similar. Hence, in order to simplify the visual representation, it was decided to report in Figures 13.9 and 13.10 the behaviour of a building belonging to the oldest construction period for both geographical areas, as it turned out to be the one that best shows the effects due to the presence of the green roof. The graphs relative to all the 16 analysed buildings are reported in Figures 13.A.1 – 13.A.12 in supporting information.

As previously mentioned, an important indicator when assessing the indoor comfort levels is represented by the PMV. For this reason, it was decided to report a comparison between the monthly PMV average (solid hatched green and black bars) and the relative peak values (white bars with dashed border) for ST and GR.

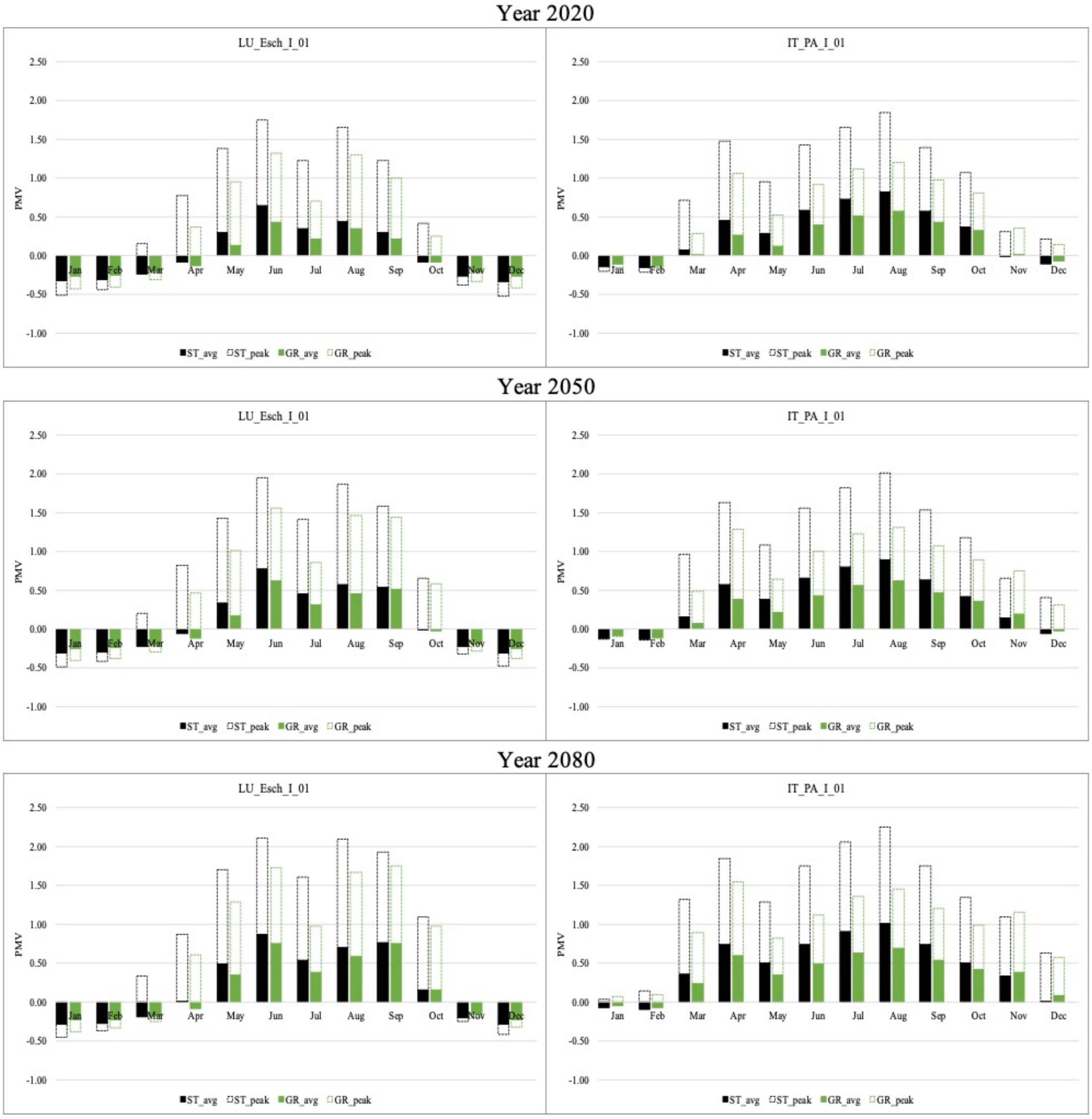


Figure 13.9. Comparison between PMV average and peak values in the three considered years (2020 on the top, 2050 in the middle and 2080 on the bottom) for Esch-sur-Alzette (left) and Palermo (right) reference buildings.

Figure 13.9 shows the obtained results for Esch-sur-Alzette (left hand side) and Palermo (right hand side). Values of the PMV around zero indicate a neutral thermal feeling, while negative and positive values indicate discomfort due to cold and hot feeling, respectively.

By looking at the differences in the obtained PMV average values with and without the presence of the green roof, especially those relative to the summer periods, it arises that the presence of the green roof reduces PMV average values. Such differences are more evident for the buildings sited in Palermo where (for almost every construction period, see SI), according to the standard currently in force for the design of the indoor environment [EN, 2019], the presence of the green roof contributes to shift the indoor thermal environmental conditions from an acceptable-moderate level of expectations (PMV ≥ 0.5) to a moderate-normal level of expectation (PMV ≤ 0.5). A similar behaviour is also noticeable for the building in Esch-sur-Alzette belonging to construction periods I and II, while the other buildings' categories do not seem to be influenced by the presence of a green coverage. In other words, the presence of the green roof in most cases contributes to bring the building (specifically the top floors) towards better comfort conditions.

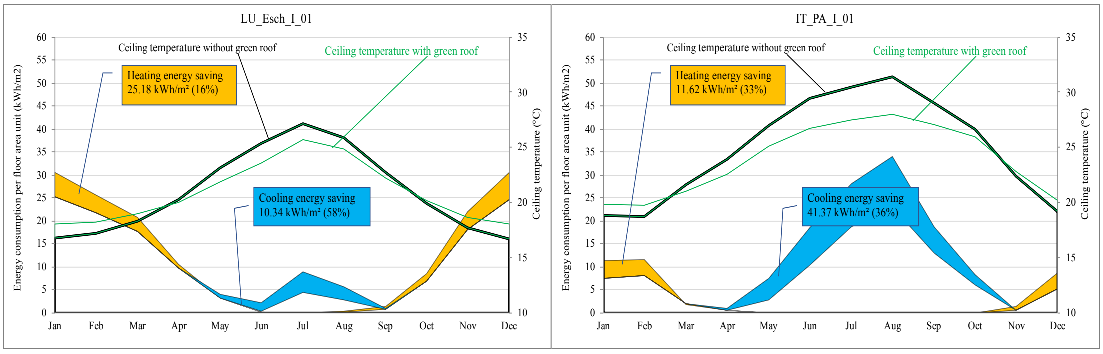
Moreover, by analysing Figure 13.9, it can also be seen how, notwithstanding the above-mentioned general positive effects, some critical issues emerged in the transition months (April for Esch-sur-Alzette and November for Palermo), for which the standard roof seems to perform slightly better than the green roof. This effect, which needs to be better investigated, is probably due to the additional thermal inertia that the presence of the green roof brings to the structure, which may slow down the response of the green roof compound to the changes of climatic conditions occurring in the transition periods of spring and autumn.

Other than the PMV, another significant parameter when assessing the indoor comfort levels is represented by the ceiling temperature. In Figure 13.10 a comparison between the ceiling temperatures with (green line) and without (black line) the presence of the green roof is showed.

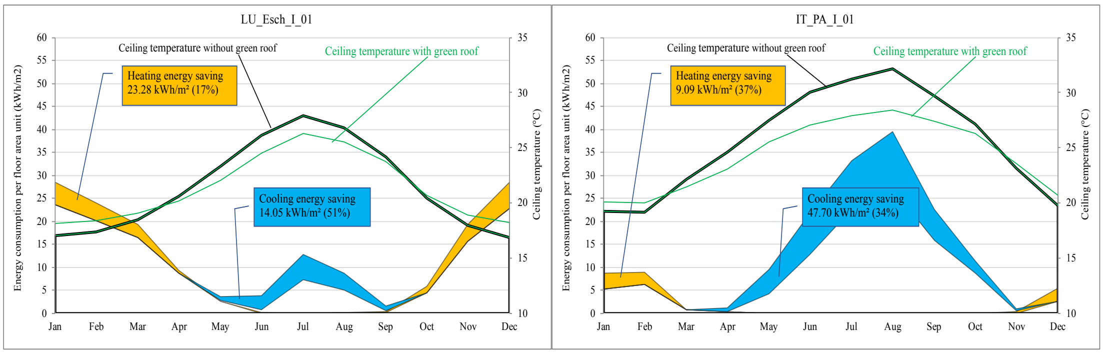
Figure 13.10 highlight the positive effects due to the presence of the green roof, which, with respect to the standard roof, allows maintaining higher ceiling temperatures in winter and lower ceiling temperatures during summer. Specifically, ceiling temperature variations comprised between 2°C (for Esch-sur-Alzette) and 5°C (for Palermo) can be observed, without significant changes over the years.

Once again, such behaviour resulted being even more noticeable for all Palermo buildings' construction periods and Esh-sur-Alzette buildings belonging to the first two construction periods (see SI).

Year 2020



Year 2050



Year 2080

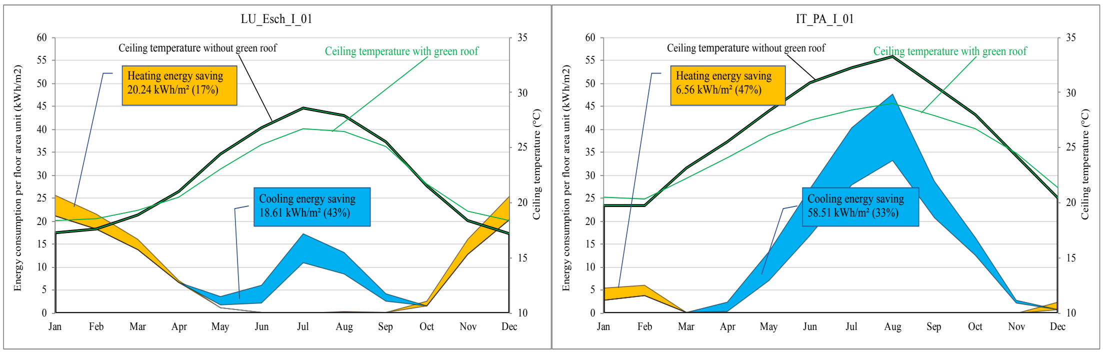


Figure 13.10. Comparison between ceiling temperatures and energy savings in the three considered years (2020 on the top, 2050 in the middle and 2080 on the bottom) for Esch-sur-Alzette (left) and Palermo (right) reference buildings.

As reported in Figure 13.10, the noticed temperature differences also had an impact on the energy consumption, which is reported in the graphs, in terms of heating and cooling energy savings, as solid hatched yellow and blue area, respectively. In particular, for Esch-sur-Alzette, the energy savings obtainable during summer are greater (~50%) than those related to the winter period (~20%), and are comparable over the years. As for Palermo, it can be noted how for the years 2020 and 2050 there is almost no difference between heating and cooling energy savings (3-4% difference), while for the year 2080 the difference is more accentuated (14% difference), with winter savings resulting greater than summer ones. Once more, similar considerations can be drawn looking at the outcomes of buildings belonging to all construction periods (see SI).

13.4.2 Extension to the two considered building stocks for the different future scenarios

The simulation model, previously applied to a single building level, was subsequently extended, for each of the SSPs described in section 13.3.3, to the current fraction of the considered Esch-sur-Alzette and Palermo (Bandita) building stocks, increased by the future development of the surfaces as described in section 13.3.3.2. To this end, it was assumed that new buildings will have the same constructive characteristics of the surveyed buildings belonging to the most recent construction periods (Tables 13.5 and 13.6). In addition, it was supposed that over the years 2050 and 2080 a percentage of the existing buildings will be subjected to retrofit interventions; in particular, the retrofit percentages reported in Table 13.9 have been considered (assuming a 1% as energy renovation rate [EU, 2019]).

Table 13.9. Buildings retrofit percentages for Esch-sur-Alzette and Palermo.

2020	2050		2080		
no retrofit	no retrofit	retrofit_2050	no retrofit	retrofit_2050	retrofit_2080
100%	75%	25%	55%	25%	20%

Moreover, to take into account the trend of technological improvement of the building envelope components' energy performance, their transmittances have been upgraded for the new buildings and for the retrofitted ones for years 2050 and 2080. These upgrades have been assessed assuming for each component a maximum improvement of thermal specific resistance of 1 m^2K/W [IRP, 2017] with respect to their respective best values, and hypothesizing that these maximum improvements take place in the year 2100. Hence, using the values of transmittance referred to the building construction year and utilizing a logistic function as an interpolation curve, the new transmittances for each envelope component have been estimated for the years 2050 and 2080.

In order to draw some considerations on how the presence of green roofs can affect the buildings energy behaviour in the two very different considered climatic contexts, Table 13.10 summarizes, and shows a comparison between, the comprehensive results obtained for the three years (2020, 2050 and 2080) and the five socioeconomic pathways (SSP1, SSP2, SSP3, SSP4 and SSP5).

Table 13.10. Comparison between the energy behaviour of buildings in Esch-sur-Alzette and Palermo (Bandita).

SSPs	Year	Esch ST	Esch GR	Esch	Palermo ST	Palermo GR	Palermo
		Qheat (MWh)/Qcool (MWh)	Qheat (MWh)/Qcool (MWh)	var % / var %	Qheat (MWh)/Qcool (MWh)	Qheat (MWh)/Qcool (MWh)	var % / var %
-	2020	61 900 / 8 235	58 994 / 7 179	-4.7 / -12.8	17 583 / 78 505	15 454 / 72 660	-12.1 / -7.4
SSP1	2050	83 778 / 21 939	81 769 / 20 452	- 2.4 / - 6.8	11 548 / 101 507	9 815 / 94 415	-15.0 / -7.0
	2080	71 755 / 36 936	70 661 / 35 263	- 1.5 / - 4.5	5 682 / 129 721	4 525 / 121 277	-20.4 / -6.5
SSP2	2050	79 977 / 20 971	77 996 / 19 526	- 2.5 / - 6.9	10 511 / 94 426	8 964 / 88 193	-14.7 / -6.6
	2080	67 641 / 34 980	66 582 / 33 379	- 1.6 / - 4.6	5 162 / 120 473	4 135 / 113 075	-19.9 / -6.1
SSP3	2050	49 171 / 13 122	47 419 / 12 017	- 3.6 / - 8.4	10 511 / 94 426	8 964 / 88 193	-14.7 / -6.6
	2080	36 294 / 20 079	35 497 / 19 018	- 2.2 / - 5.3	5 162 / 120 473	4 135 / 113 075	-19.9 / -6.1
SSP4	2050	69 599 / 18 327	67 696 / 16 997	- 2.7 / - 7.3	10 511 / 94 426	8 964 / 88 193	-14.7 / -6.6
	2080	53 322 / 28 173	52 383 / 26 819	- 1.8 / - 4.8	5 162 / 120 473	4 135 / 113 075	-19.9 / -6.1
SSP5	2050	127 129 / 32 983	124 798 / 31 019	- 1.8 / - 6.0	15 946 / 131 549	13 427 / 120 814	-15.8 / -8.2
	2080	144 457 / 71 496	142 753 / 68 570	- 1.2 / - 4.1	8 454 / 178 966	6 602 / 164 953	-21.9 / -7.8

Table 13.10 shows the thermal energy consumption absolute values at urban level for the two considered contexts: the city center of Esch-sur-Alzette and the Bandita district of Palermo. In particular, the values for the ST, those for the GR and a comparison between the two (var% / var%) are reported.

As it was to be expected, given the climatic zone (latitude) in which the two examined sites are located, higher figures for heating were observed for Esch-sur-Alzette, while for Palermo the greater ones are those relating to cooling. In fact, the positive trend in energy usage is due to both the increase in population, and therefore in the number of buildings (Table 13.3 and Table 13.4), and the change in external climatic conditions. In particular, the rise in temperatures linked to climate change means that the increase in the values referred to heating is less extensive than the corresponding increase for cooling.

Finally, in the last part of this section an annual estimation of the CO_2 emissions is reported. Table 13.11 summarize the data related to the emissions ($kgCO_{2eq}\cdot m^{-2}$) ascribable to the ST roofs and the relative percentages of reduction achievable thanks to the presence of GR, for all the considered years and SSPs.

Table 13.11. Annual ST CO_2 emissions and relative savings due to the presence of GR.

		Esch-sur-Alzette				**Palermo**			
		Heating		**Cooling**		**Heating**		**Cooling**	
SSPs	**Year**	**ST**	**GR**	**ST**	**GR**	**ST**	**GR**	**ST**	**GR**
		tCO_{2eq}	**tCO_{2eq} saving**	**tCO_{2eq}**	**tCO_{2eq} saving**	**tCO_{2eq}**	**tCO_{2eq} saving**	**tCO_{2eq}**	**tCO_{2eq} saving**
-	2020	18913.99	888.07	1180.30	151.28	5372.55	650.63	12560.88	935.23
SSP1	2050	25598.68	613.76	1389.47	94.16	3528.59	529.47	6767.15	472.82
	2080	21925.06	334.26	2093.03	94.77	1736.32	353.54	7783.28	506.65
SSP2	2050	24437.35	605.12	1328.15	91.50	3211.82	472.83	6295.08	415.57
	2080	20668.14	323.71	1982.22	90.75	1577.29	313.67	7228.39	443.90
SSP3	2050	15024.38	535.09	831.09	69.99	3211.82	472.83	6295.08	415.57
	2080	11089.83	243.38	1137.81	60.13	1577.29	313.67	7228.39	443.90
SSP4	2050	21266.48	581.53	1160.71	84.26	3211.82	472.83	6295.08	415.57
	2080	16292.83	287.02	1596.50	76.76	1577.29	313.67	7228.39	443.90
SSP5	2050	38844.99	712.30	2088.95	124.43	4872.53	769.79	8769.96	715.70
	2080	44139.68	520.57	4051.44	165.80	2583.12	565.82	10737.97	840.78

The data reported in Table 13.11 are intended to simply provide an indicative information relating to the CO_2 emission savings for the buildings sector that could be obtained by implementing this type of intervention.

13.4.3 Effectiveness of vegetated roofs in enhancing buildings' future climate resilience

The analysis carried out in this work was intended to highlight the effectiveness of green roofs as a sustainable tool aimed at improving the resilience of (new and existing) buildings to future climate changes conditions (also in light of the heatwaves that are increasingly intensifying), mainly in terms of indoor comfort and energy consumption.

Looking at the PMV and ceiling temperature results (Figure 9 and Figure 10), despite a progressive slight worsening of the indoor comfort conditions across the years is observed, it can be noted how the green roof still allows to attenuate the effects due to future increase in external temperature linked to climate change.

The same considerations can be made with respect to the energy aspect (Figure 10 and Table 10). Although the increasing outdoor temperatures lead to an increase in the cooling loads, the presence of the green roof brings an advantage in terms of energy savings compared to what would be obtained by maintaining a standard roof.

In particular, from the comparison between PMV peak values, ceiling temperatures and energy consumption absolute values (Figure 9, Figure 10 and Table 10), it is evident how the green roof technology, in addition to providing an initial advantage in 2020, also allows for future mitigation for the 2050 and 2080 time-frames. Hence, as also shown in Figure 11, this technology seems to represent a valid option in order to improve the resilience of buildings to global climate change, at least in the climatic zones that have been the object of this study.

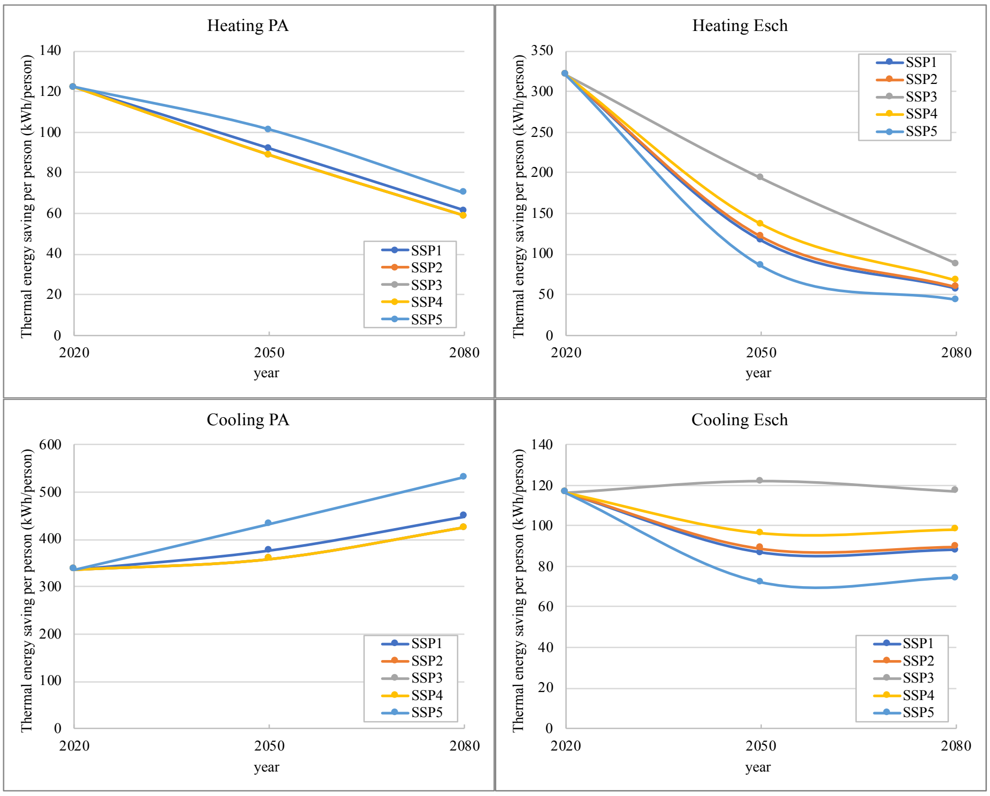


Figure 13.11. Comparison between the heating and cooling thermal energy savings per person trends (2020-2050-2080) in the five SSPs for Esch-sur-Alzette (right) and Palermo (left).

To give an idea of the order of magnitude of the energy consumption order of magnitude, the graphs in Figure 13.11 show, for the various considered scenarios, the thermal load variations in KWh per person related to the presence of the green roofs compared to the 2020 standard roofs reference values: heating Esch-sur-Alzette = 6840 KWh·person^{-1}, cooling Esch-sur-Alzette = 910 KWh·person^{-1}, heating Palermo = 1010 KWh·person^{-1} and cooling Palermo = 4510 KWh·person^{-1}.

In Figure 11 the lower curves refer to the scenarios for which there is no increase in the population, and therefore neither in the number of buildings (Table 13.3 and Table 13.4), so the positive effects are only ascribable to the presence of green roofs on existing buildings. On the other hand, when there is an increase in the population, and consequently in the number buildings, the cumulative positive effects are due, not only to the presence of green roofs, but also to the fact that new buildings inherently behave better than the existing ones (due to improved technology).

Climate change leads to a rise in temperatures, so in the future the beneficial effects due to the presence of the green roofs may tend to decrease. In fact, looking at Figure

11 it can be observed that for both sites there is a reduction in heating energy consumption (heating load), which decreases across the years. The same cannot be said for the reduction in consumption related to cooling (cooling load). In fact, while for Palermo such reduction becomes more and more important across time, for Esch-sur-Alzette an opposite trend can be observed. This circumstance is linked to the influence that the different geographical position of the two cities has on their respective climates.

Overall, however, one can say that in the examples we have explored, the presence of the green roofs makes the buildings more resilient to the increase of outdoor temperature.

13.5 Conclusions

The aim of the research work here presented was investigating on vegetated roofs used as passive envelope components aimed at improving buildings resilience at the urban scale, since they represent a very common solution in recent years.

The outcomes of the analysis showed that, with respect to standard roofs, green roofs allow a reduction of the energy consumption (for both heating and cooling loads), and an improvement of the indoor thermal comfort conditions (in terms of PMV and ceiling temperatures), acting as relievers of the increasingly high outdoor temperatures that are the result of climate change.

Thanks to the above-mentioned thermo-hygrometric benefits (which, however, can sometimes be questionable in some particular types of climate, as literature has showed), green roofs can also help reduce the size of the technical plants and limiting their use. This has in turn a positive impact on the outdoor urban environment inducing various benefits such as the reduction of CO_2 emissions (as confirmed by the obtained results) and the mitigation of the UHI effect, as well as other advantages in terms of air purification and aesthetic aspects.

Furthermore, as claimed in previous studies, green roofs also have a beneficial effect in terms of water runoff reduction, acting both on (although limitedly) water filtration and on flooding limitation [Babí Almenar et al., 2021, Castiglia Feitosa & Wilkinson, 2016, Keeler et al., 2019, Talebi et al., 2019]. This positive effect of green roofs is particularly important in view of the more and more frequent heavy rainfall events causing massive flooding, like the one that has hit the city of Palermo on 15 July 2020 [https://www.youtube.com/watch?v=C_P2dqSuDig].

In conclusion, the performed study made it possible to examine the different impact that climate change (in terms of future temperature increase) and predicted socioeconomic and demographic trends have on the effectiveness of green roofs in enhancing buildings resilience at urban level, also as a function of the geographical context.

The applied methodology represents a first step in the development of procedures meant to assess strategies and solutions aimed at strengthen the resilience of clustered buildings, to be further explored and deepened, by also including the economic aspects.

Concerning these latter, other studies [Blackhurst et al., 2010, Feng & Hewage, 2018, Marvuglia et al., 2020 (b)] performed at the single building level have indeed demonstrated that, although green roofs are often not cost effective on private single houses, they become a more competitive solution on multifamily, public and commercial buildings, especially when social (attenuation of the UHI, greenhouse gases emissions reduction, and storm-water runoff reduction) and aesthetic benefits are also taken into account. It would, then, be interesting to estimate the green roofs economic behavior in a wider urban context.

Chapter 13 Acknowledgment

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Chapter 13 Appendices

Supporting Information – SI

As already mentioned in Section 13.3.4, Table 13.A.1.a, Table 13.A.1.b., Table 13.A.2 and Table 13.A.3 summarize the construction features of interest for the selected buildings of the two towns, where the specifics elements materials have been coded according to the UNI TR 11552 standard [UNI, 2014 (b)].

Regarding the external walls’ characteristics, in Table 13.A.1.a the sequence of materials reported in each row indicates the layers’ order going from the external to the internal ones. In Table 13.A.1.b, instead, each row (which refers to a different construction period) shows the succession of the layers going from the inside to the outside.

Concerning the schedule used for HVAC system, it is here reported:

- The HVAC running periods are 15 October to 14 April and 15 April to 14 October for heating and for cooling circuit, respectively [UNI, 2016].
- The setpoint temperatures are 21°C and 25°C for heating and for cooling system, respectively. These values have been chosen adding up or subtracting 1°C from the heating season minimum value (20°C) and cooling season maximum value (26°C) suggested by [UNI, 2019] in table B.5 for Category II.

Table 13.A.1.a. Construction features for the selected buildings in Esch-sur-Alzette (a).

Construction period	Building ID	Glazing type	Opaque elements materials (1)			
			External walls			
< 1949	LU_Esch_I_01	single	lime mortar	calcar stone	gypsum	
	LU_Esch_I_02	single		brick	gypsum	
1950-1968	LU_Esch_II_03	single	lime mortar	slag cement block	gypsum	
	LU_Esch_II_04	single				
1969-1994	LU_Esch_III_05	double	lime mortar	concrete block	insulation mix	gypsum
	LU_Esch_III_06	double				
> 1995	LU_Esch_IV_07	double	lime mortar	concrete block	insulation mix	gypsum
	LU_Esch_IV_08	double				

Table 13.A.1.b. Construction features for the selected buildings in Esch-sur-Alzette (b).

Opaque elements materials (2)										
Roof						Ground floor				
wood (hard)	wood (board)	insulation mix	bitumen	tiles		insulation mix	wood (board)	cement screed	tiles	
lime mortar	reinforced concrete	cement screed	bitumen	gravel		reinforced concrete	cement screed	bitumen	tiles	
lime mortar	reinforced concrete	insulation mix	cement screed	bitumen	gravel	reinforced concrete	cement screed	insulation mix	bitumen	tiles
lime mortar	reinforced concrete	insulation mix	cement screed	bitumen	gravel	reinforced concrete	cement screed	insulation mix	bitumen	tiles

Table 13.A.2. Construction features for the selected buildings in Palermo.

Construction period	Building ID	Glazing type	Opaque elements materials codes* from *UNI TR 11552 standard* [UNI, 2014 (b)]			
			External walls	Floor	Ground floor	Roof
< 1945	IT_PA_I_01	double	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
	IT_PA_I_02	single	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
1946-1971	IT_PA_II_03	double	*MCO 03*	*SOL 02*	*SOL 08*	*COP 01*
	IT_PA_II_04	double	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
1972-1991	IT_PA_III_05	double	*MCO 03*	*SOL 02*	*SOL 07*	*COP 01*
	IT_PA_III_06	double	*MCO 03*	*SOL 02*	*SOL 07*	*COP 01*
	IT_PA_III_07	single	*MPI 03*	*SOL 02*	*SOL 07*	*COP 01*
> 1991	IT_PA_IV_08	double	*MCO 03*	*SOL04*	*SOL 07*	*COP 01*

Table 13.A.3. Opaque elements materials' codes as reported in the UNI TR 11552 standard [UNI, 2014 (b)].

Element	Code	Materials' sequence
External wall	*MPI 03*	Internal plaster Tuff blocks External plaster
	MCO 03	Internal plaster Concrete blocks External plaster
Floor slab	*SOL 02*	Internal stoneware floor Cement mortar Lightweight concrete screed Cement mortar Concrete slab External plaster
	SOL 04	Internal stoneware flooring Cement mortar Lightweight concrete screed Cement mortar Reinforced concrete Concrete slab External plaster
Ground slab	*SOL 07*	Internal stoneware flooring Cement mortar Ordinary concrete screed Reinforced concrete (casting) External plaster
	SOL 08	Internal stoneware flooring Cement mortar Lightweight concrete Scree - river pebbles
Roof	*COP 01*	Internal plaster Concrete slab Reinforced concrete Cement mortar Ordinary concrete screed Bituminous waterproof membrane

Monthly PMV average and peak values for all analysed buildings in Esch-sur-Alzette, for the years 2020 (Figure 13.A.1), 2050 (Figure 13.A.2) and 2080 (Figure 13.A.3):

Figure 13.A.1. Monthly PMV average and peak values for all analysed buildings in Esch-sur-Alzette, for the year 2020.

Figure 13.A.2. Monthly PMV average and peak values for all analysed buildings in Esch-sur-Alzette, for the year 2050.

Figure 13.A.3. Monthly PMV average and peak values for all analysed buildings in Esch-sur-Alzette, for the year 2080.

Monthly PMV average and peak values for all analysed buildings in Palermo, for the years 2020 (Figure 13.A.4), 2050 (Figure 13.A.5) and 2080 (Figure 13.A.6):

Figure 13.A.4. Monthly PMV average and peak values for all analysed buildings in Palermo, for the year 2020.

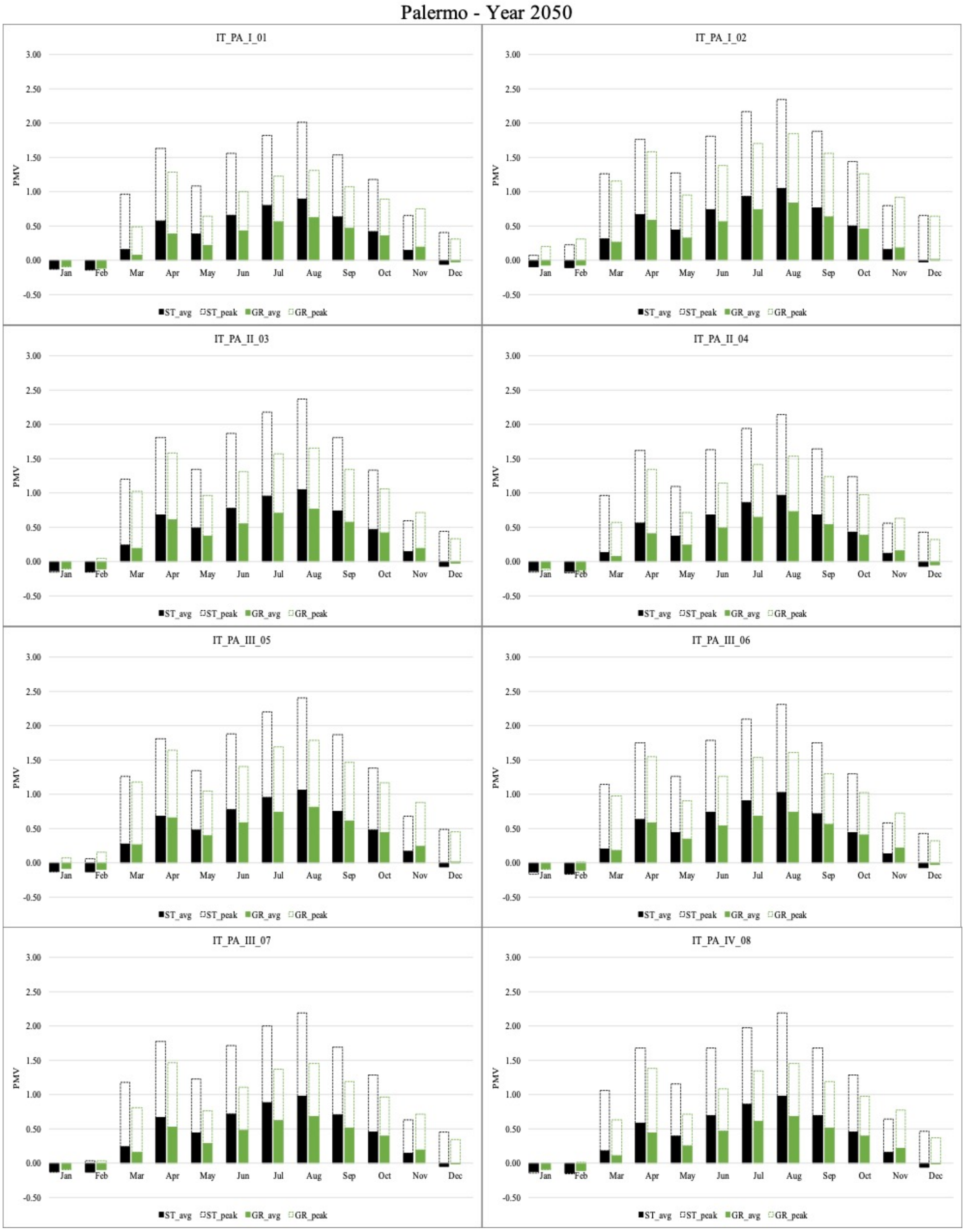

Figure 13.A.5. Monthly PMV average and peak values for all analysed buildings in Palermo, for the year 2050.

Figure 13.A.6. Monthly PMV average and peak values for all analysed buildings in Palermo, for the year 2080.

Comparison between standard roof and green roof ceiling temperatures and energy savings (heating and cooling) for all analysed buildings in Esch-sur-Alzette, for the years 2020 (Figure 13.A.7), 2050 (Figure 13.A.8) and 2080 (Figure 13.A.9):

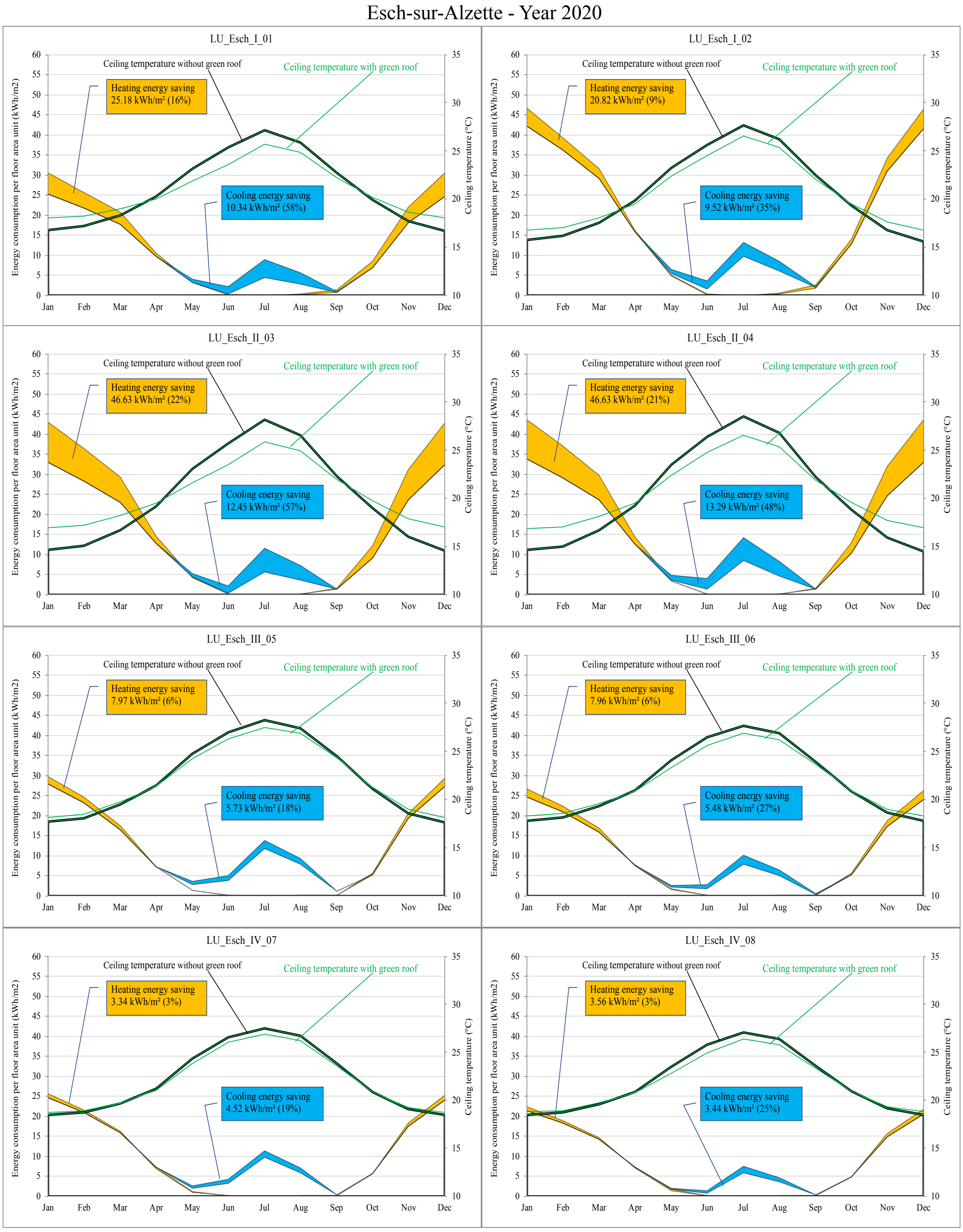

Figure 13.A.7. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Esch-sur-Alzette, for the year 2020.

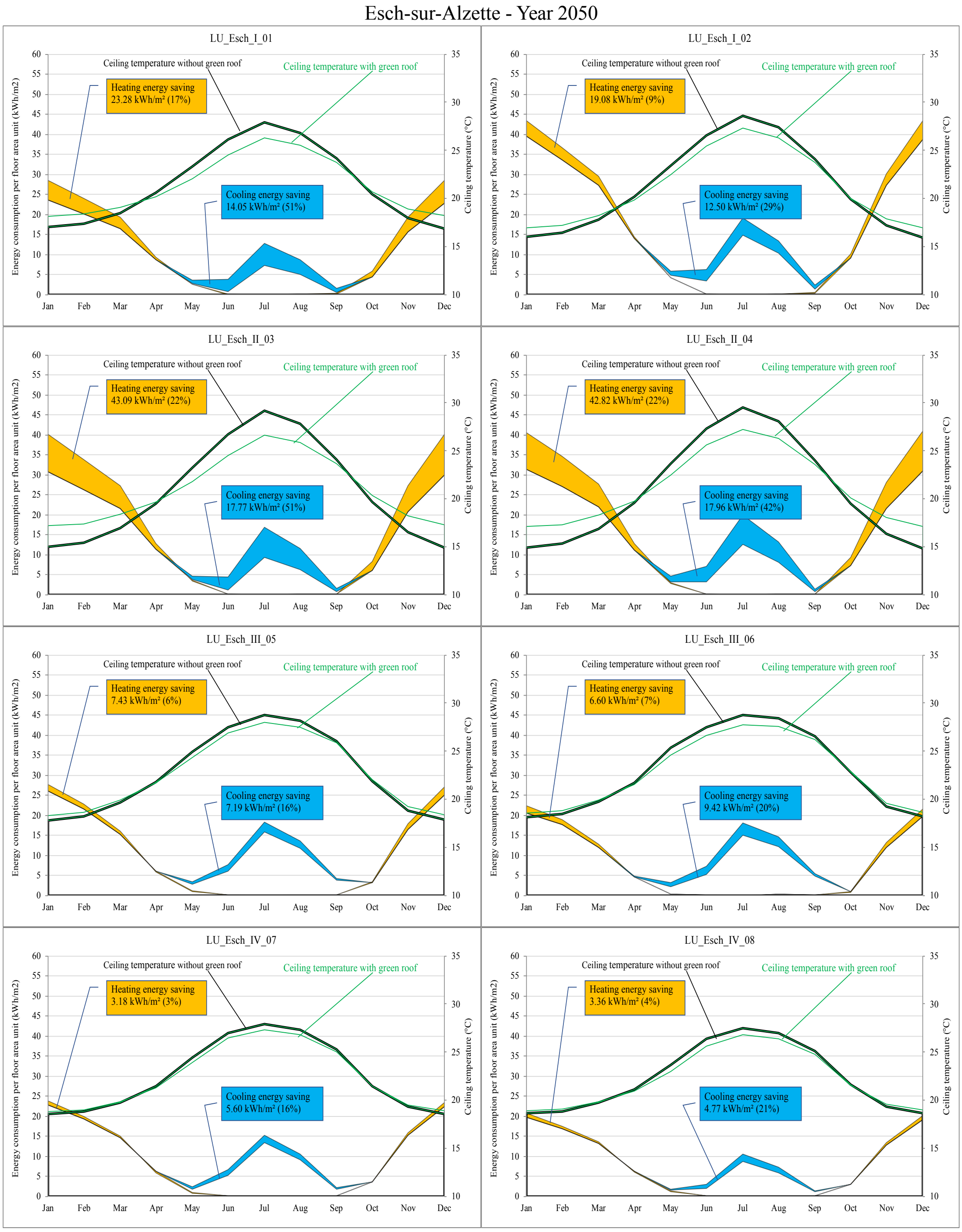

Figure 13.A.8. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Esch-sur-Alzette, for the year 2050.

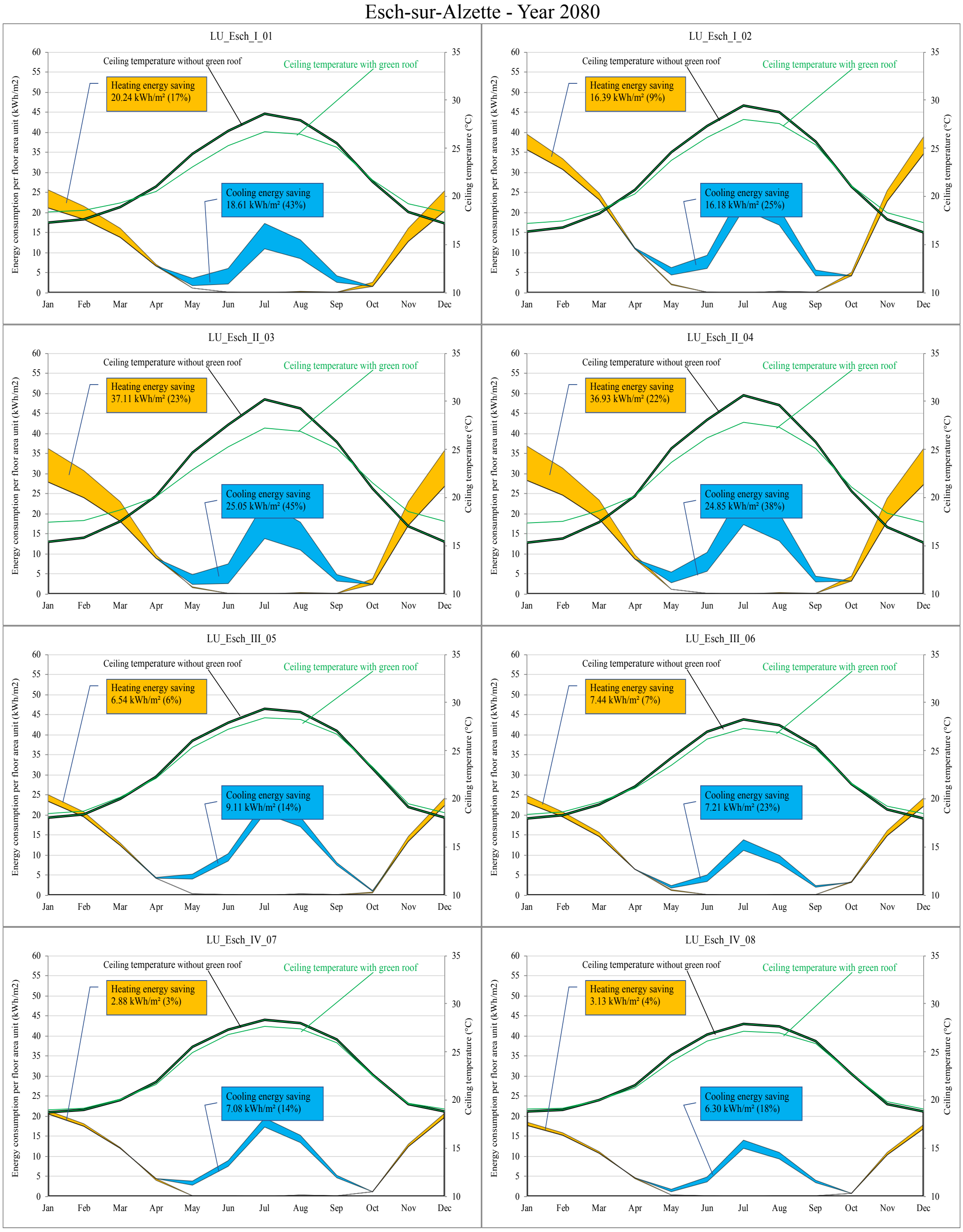

Figure 13.A.9. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Esch-sur-Alzette, for the year 2080.

Comparison between standard roof and green roof ceiling temperatures and energy savings (heating and cooling) for all analysed buildings in Palermo, for the years 2020 (Figure 13.A.10), 2050 (Figure 13.A.11) and 2080 (Figure 13.A.12):

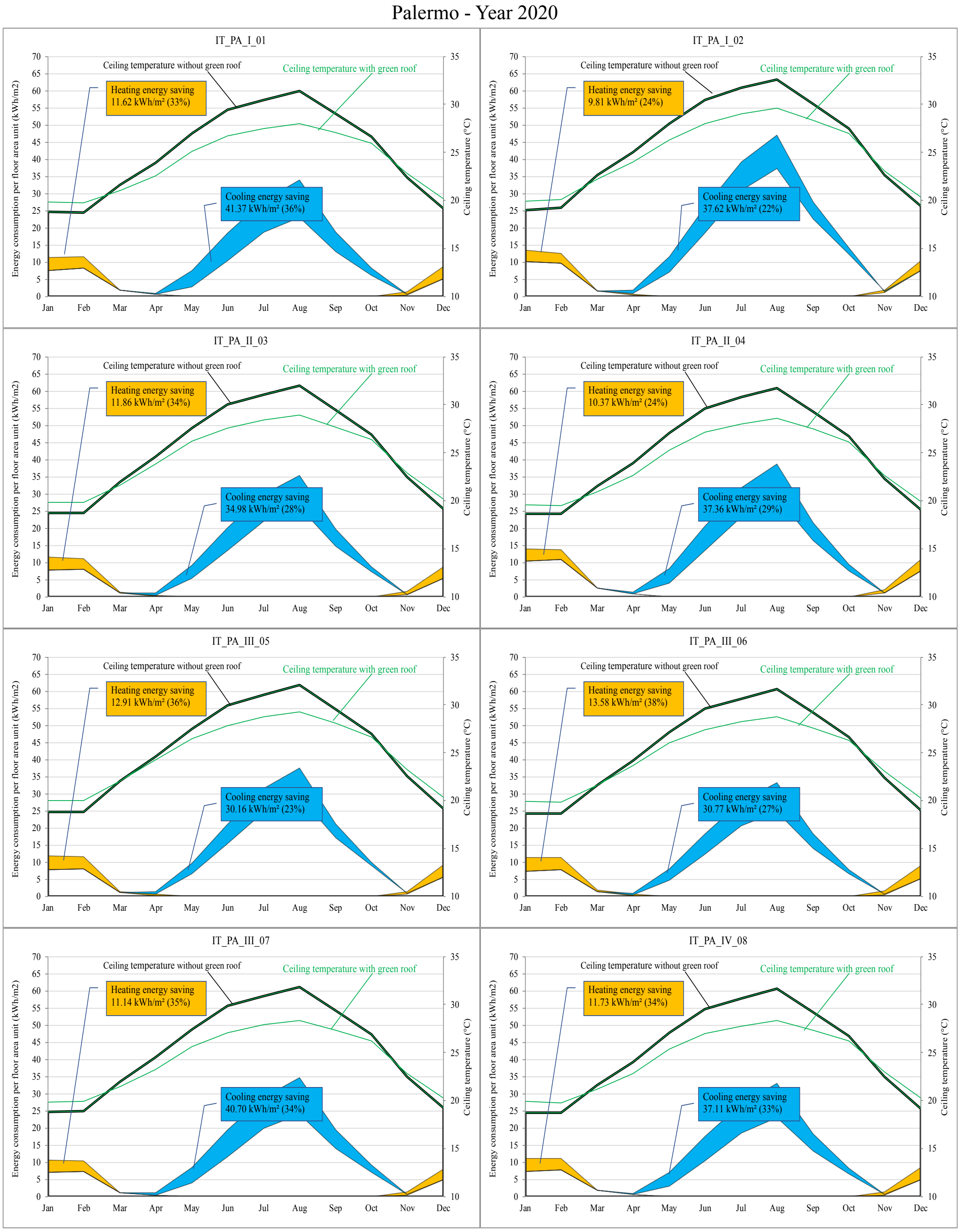

Figure 13.A.10. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Palermo, for the year 2020.

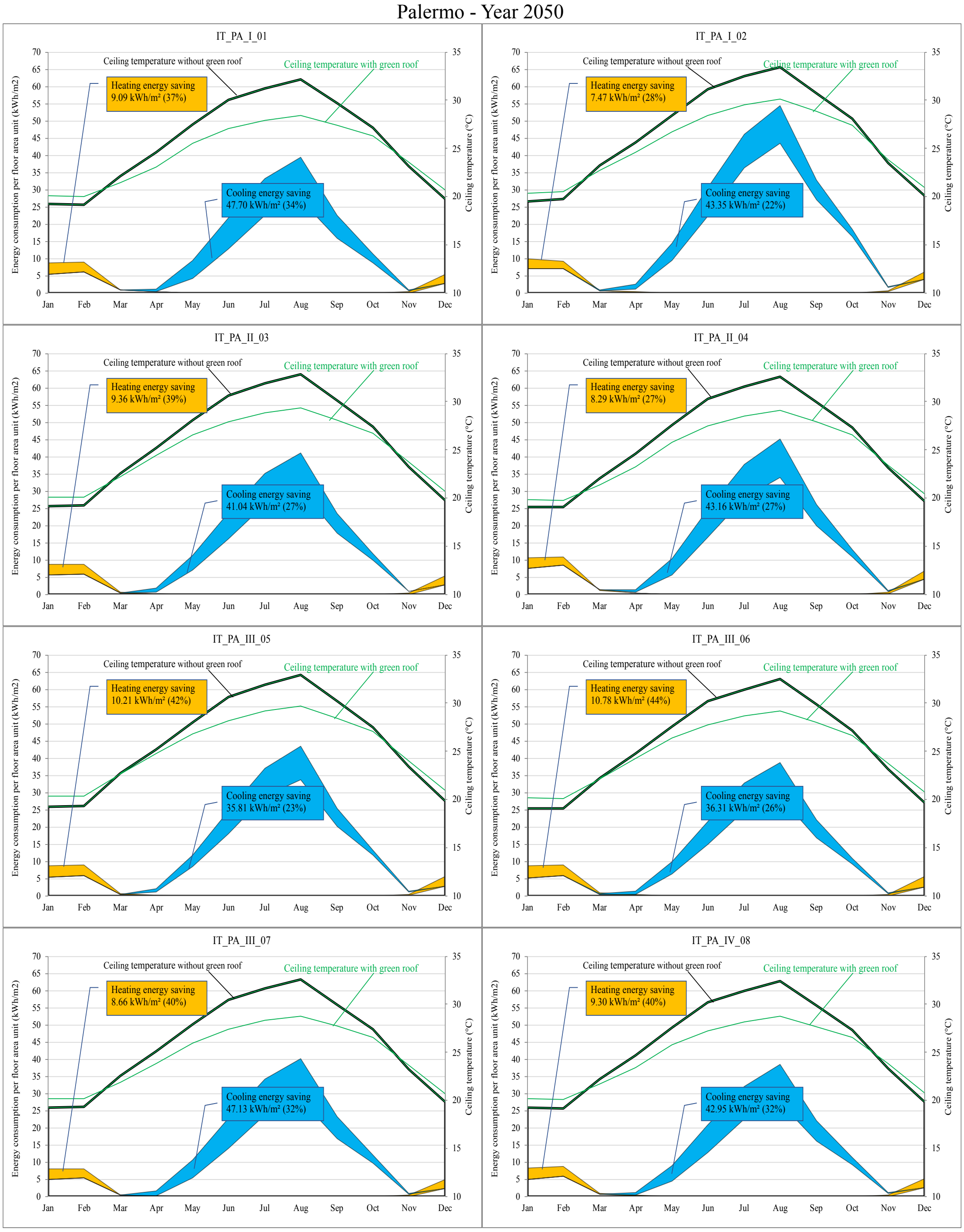

Figure 13.A.11. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Palermo, for the year 2050.

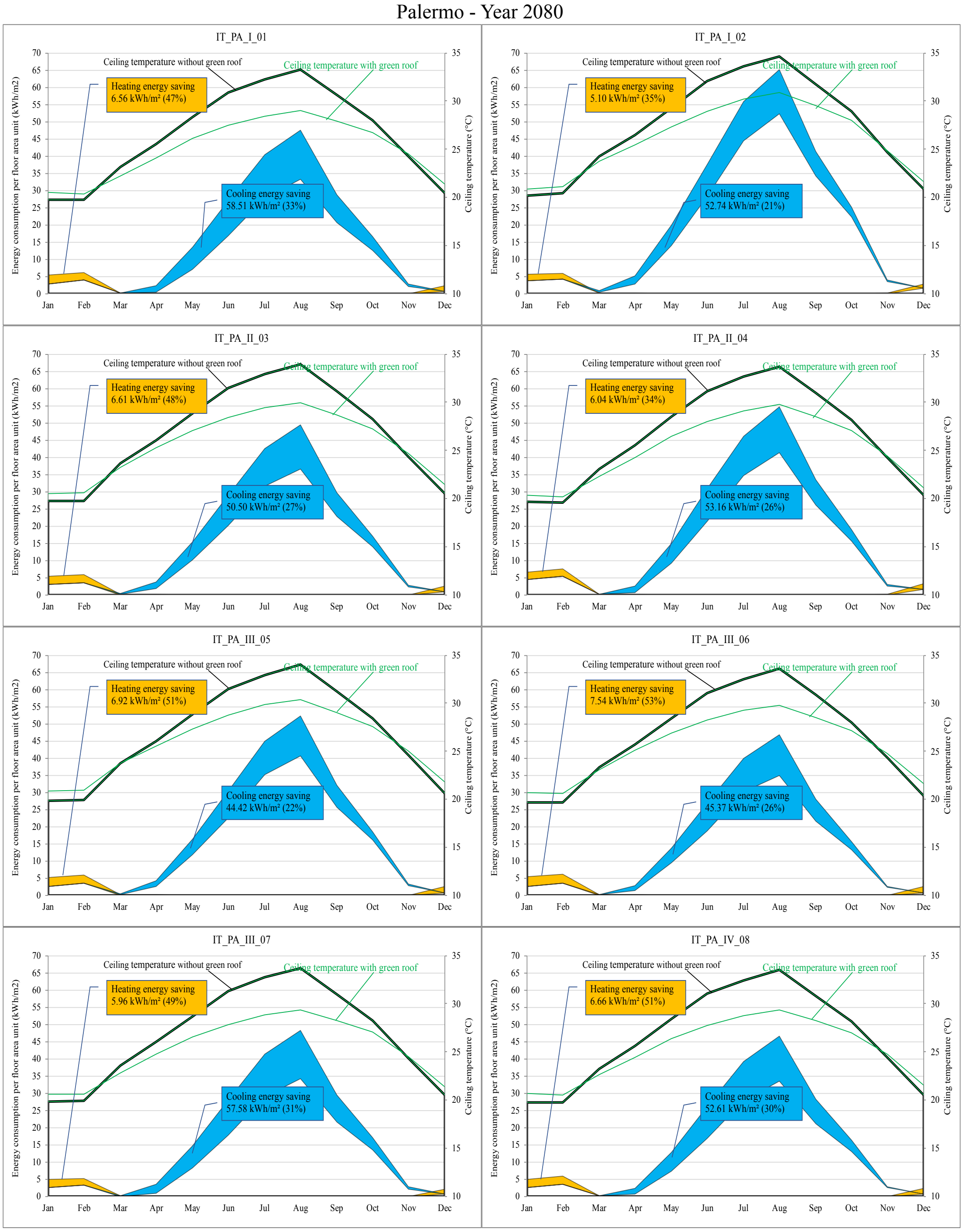

Figure 13.A.12. Comparison between standard roof and green roof ceiling temperatures and energy savings for all analysed buildings in Palermo, for the year 2080.

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PART II – Results and Findings

The studies showed in this part of the dissertation, aimed at analysing the resilience potential of clustered group of buildings, put in evidence the following main two aspects:

- the importance of the availability of a tool able to provide a comprehensive evaluation of the energy and environmental performances related to a set of intervention applied to wide urban areas;
- the different impact that climate change (mostly in terms of temperature increase) and future estimated socioeconomic and demographic trends have on the effectiveness of interventions aimed at enhancing urban resilience, also depending on the geographic climate context.

PART II – Conclusion

The research work shown in this second part of the dissertation started from the intent to widen the the concepts of energy efficiency and environmental performance of buildings going from the single structure (object of Part I) to a group of them, in view of achieving a more comprehensive urban resilience.

The main results and findings, which have been here briefly summarized, will be further discussed and contextualized in the general framework of the dissertation in the conclusive Part IV.

The outcomes have put in evidence the importance of the context in which such solutions are implemented, in terms of its influence on both energy and environmental yields.

Related to this, the aspect regarding the peculiarities characterizing the contexts in which one operates, in terms of building typologies, will be the subject of the next part of the dissertation.

PART III – Tertiary Buildings: Historical and Tourism

This part of the dissertation concentrates on two specific categories of buildings representative of the Italian cultural heritage for historic as well as for economical reasons, i.e. historical and tourism buildings, and it is divided into two sections:

- SECTION III.A – Historical Buildings: Museums and Exhibition Halls
- SECTION III.B – Tourism Buildings: Energy Savings and Quality Brands

PART III – Tertiary Buildings: Historical and Tourism

SECTION III.A – Historical Buildings: Museums and Exhibition Halls

In this section a specific attention was given to a particular type of structure that represent an important reality in the Italian construction panorama, for both economic and historic reasons, i.e. historical buildings, precisely those used as museums and/or exhibition halls.

In such scenarios, in fact, when considering possible energy interventions, it is important to adequately control the indoor microclimate parameters so as to guarantee the preservation of the valuable hosted cultural goods, besides ensuring the visitors' comfort. Purposely, this section presents a comprehensive operative damage risk indicator concerning the museums' indoor environmental conditions.

This section of the dissertation encompasses one chapter:

Chapter 14 - Two operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical service providers

Chapter 14 - Two operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical services providers

This chapter consists in the following journal paper:
Cirrincione, L., Nucara, A., Peri, G., Rizzo, G., Scaccianoce, G., Two operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical services providers, (2020) Journal of Cultural Heritage, 41, pp. 200-210.
DOI: https://doi.org/10.1016/j.culher.2019.07.012

Abstract: The purpose of Heating, Ventilating and Air-Conditioning (HVAC) systems in museums is to properly control important microclimate parameters; such systems, in fact, apart from ensuring the visitors' wellbeing, are requested to guarantee suitable indoor conditions for the proper conservation of the important cultural goods hosted by museums. Hence, in case of disservice, or interruption due to maintenance interventions, it is important to quantify the economic damage induced to exhibited and/or stored works of art (or even to the building museum itself). Accordingly, it is essential to guarantee the shortest possible period of disservice during which probable damages for the works of art could occur.
Since curators are the most relevant subjects committed to properly run the museum, also for what concerns the indoor environmental conditions, the aim of this work is to propose two new comprehensive operative damage risk indicators to support curators in negotiating the stipulation of contracts with the external companies in charge of the management of the HVAC system, in order to preserve the works of art. Particularly, these indicators try to integrate, into the contracts, economic considerations related to the system's disservice period and/or planned interruptions.
The feasibility of the proposed new indicators has been checked by means of an example application involving the "Museo Regionale" of Palermo (Italy).

Keywords: Works of art preservation – Risk Indexes – Environmental conditions – Museums – HVAC management and maintenance service contract – Economic cost.

14.1 Introduction

The purpose of Heating, Ventilating and Air-Conditioning (HVAC) systems is to properly control important microclimate physical parameters: such role is even more important in museums, since both the visitors' wellbeing and the preservation of works of art must be addressed [1, 2]. Particularly, in case of historical buildings, when considering strategies and technologies to adopt in order to optimize their energy performance [3, 4], the aspect regarding the compatibility between providing appropriate thermal performances and maintaining the architectural integrity of the building must be considered [5, 6].

It must be noted that the above-cited requirements can be sometimes controversial, since the environmental conditions required to preserve the artefacts could not be able to guarantee people comfort at the same time [7, 8]; this issue constitutes one of the main threats to which museum collections are subjected to (i.e. inappropriate environmental conditions), when the wellbeing of visitors is put first [9, 10]. In this regard, the methods to be used for monitoring and characterizing the environmental air quality inside museums, with the aim of singling out possible common ranges for the microclimate conditions, should also be clear, easy to apply and not too invasive in order not to interfere with the visual scene [11, 12, 13].

As for the HVAC systems, other than the planned interruptions due to maintenance operations, accidentally undesired failures, causing an unwanted delay of the planned interruption times, may occur. Such drawbacks could determine unsuitable indoor microclimate conditions, with possible thermal discomfort for the museum visitors, and, most importantly, they could result in unsuitable microclimate conditions for the exhibited works of art, which could determine damages to them [14, 15]. Furthermore, different works of art (characterized by different internal parameters related to the diverse materials) generally require different environmental conditions for their proper preservation, which makes the management and control of the indoor thermal microclimate even more difficult [16, 17].

An Italian standard [18] states that curators must take the final decision regarding the setting of the proper environmental physical indoor parameters for the items exhibited in galleries and museums; in fact, the most suitable microclimatic conditions strongly depend on the history of the item itself, which the curator usually knows well. People responsible for the general running of museums (such curators indeed) are the ones called to assess effective strategies that, among other features, could limit an too frequent interruption of the HVAC system. Therefore, they must draw up suitable contracts to regulate properly the relationships with the companies in charge of the management of the museum's HVAC system [19, 20]. Specifically, the objective of a proper management of a HVAC system, other than providing a sound, energy efficient and cost-effective functioning, is to ensure the compliance with the in-force standards and regulations regarding both the comfort, health, and safety of building occupants, and the works of art preservation [21, 22].

Moreover, considering that about 40% of all non-residential buildings (of which museums are part) contract maintenance service for HVAC equipment, and as thirdparty providers become more sophisticated in selling services, building managers (such as, indeed, museums curators) need to become better-informed consumers [23]. Based on the above cited considerations, the evaluation of the physical parameters inside museums should consist not only in verifying the respect of the tolerance intervals for the preservation of the artefacts, but also in taking into account the probability with which a HVAC system malfunctioning (i.e. time during which these parameters fall outside the optimal range) may occur, which in turn could result in a risk for the artefacts themselves.

In fact, as confirmed by the previously cited literature, the relevance of risks related to the HVAC systems' disservice period is associated to their maintenance and management operations. Hence, to be effective, also from the economical point of view, an optimal maintenance and management planning should require the right combination of managerial and technical skills [24].

14.2 Research aim

This work intends to provide a tool to support curators in the stipulation of contracts with external companies ("Global Service", for instance) in charge of the management and maintenance of the HVAC systems installed in their museums, in order of optimizing the preservation of the artefacts. To accomplish this task, two new operational indicators (called OP_1 and OP_2 respectively), taking into account the technological/engineering aspect of the problem, are proposed here, which are intended as a support tool for curators to properly evaluate the planned interruptions for maintenance operations of the HVAC systems and to establish the maximum duration of acceptable disservice, also on the basis of economic operative considerations. The relevance of risks is, in fact, related to the HVAC system disservice period, that is when the system is not able to maintain assigned environmental conditions related to pre-set reference values.

Figure 14.1 shows the logical process at the base of the work carried out in this paper, with the framing of our proposal (squared in red) in the context of the above-described issue.

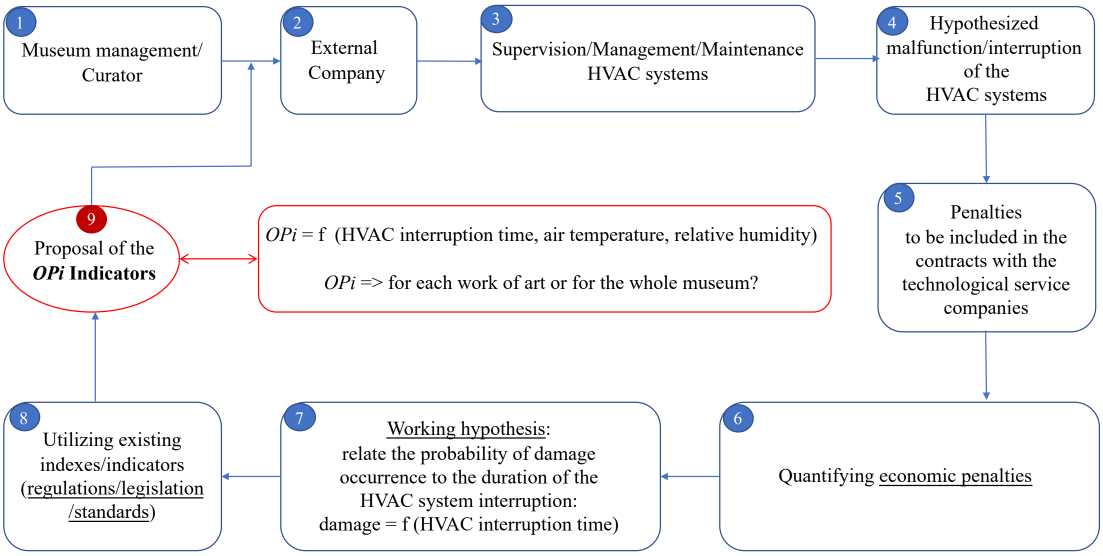

Figure 14.1. General framing of the present proposal.

As observed in Figure 14.1, the proposed indicators are based on indices and indicators already present in literature. Furthermore, an investigation into the feasibility of the two comprehensive and operational indicators has been carried out through a case study, which involved the “Museo Regionale” of Palermo (Italy).

Before introducing the two new indicators, OP_1 and OP_2, a description of both the logical procedure that guided us in the development of these indicators, and of the already existing literature indoor performance indexes, is provided below.

14.3 Methods and materials

14.3.1 The logic behind the development of a comprehensive and operative damage risk indicator

An eventual risk for the works of art is related to the total duration of the period during which the indoor physical parameters are higher or lower than the given limits established by the technical standards in force (Figure 14.2). Therefore, the probability of damage for the works of art could be reasonably related to such possible dangerous events. This should lead to an indicator dependant on monitored physical parameters on which the risk is suggested to depend.

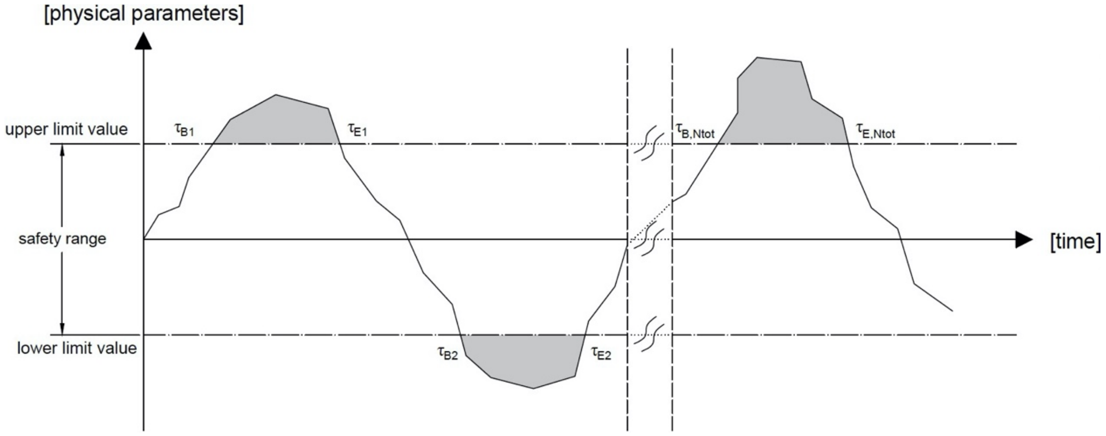

Figure 14.2. Graphical representation of the eventual risk conditions for the works of art.

Consequently, we can firstly define *n* time-dependent "damage risk" functions $p_j(\tau)$, in the intervals during which at least one of the monitored physical parameters falls outside the limits (exceedance intervals) as follows:

$$p_j(\tau), \text{ with } j = 1 \ldots n \tag{14.1}$$

where *n* represents the number of "damage risk" functions for the considered instant of time. Thereby, for each *i-th* exceedance interval, whose initial and final instants are indicated as $\tau_{Bj,i}$ and $\tau_{Ej,i}$ respectively, it is possible to define a time-independent "interval-related damage risk" function using the following formulation:

$$f_{j,i}(p_j(\tau), \tau_{Bj,i}, \tau_{Ej,i}), \text{ with } j = 1 \ldots n \text{ and } i = 1 \ldots Ns_j \tag{14.2}$$

where Ns_j is the total number of the intervals during which the exceedances occur. Furthermore, it is possible to define an "overall damage risk" function (i.e. taking into account the values of all $f_{j,i}$ functions in all the intervals) relative to the *j-th* "damage risk" function, given by:

$$g_j(f_{j,1}, f_{j,2}, \ldots, f_{j,Nsj}), \text{ with } j = 1 \ldots n \tag{14.3}$$

Finally, it will be possible to obtain a "comprehensive operative damage risk indicator" (*OP*) by means of a function that combines all the "overall damage risk" functions g_j:

$$OP = F(g_1, g_2, \ldots, g_n) \tag{14.4}$$

Generally speaking, the damage to which a given work of art is subjected is caused by different factors that could be characterized by synergic relationships. For sake of simplicity, we limited our attention to the typical physical parameters that are usually monitored in museums, namely air temperature (T) and air relative humidity (RH). In this case, we could then assume that the total risk of damage is caused by the times that the above-cited parameters fall outside the safety limits established by technical standards and regulations.

On the other hand, it must not be overlooked the fact that the curator is confronted with materials that can be organic or inorganic, and that when organic materials are involved, other than the causes of the risk of damage, the possible degradation and/or stress effects could also be used to assess such risk.

Therefore, from the perspective of someone who is intended to develop an operative damage risk indicator the approach can be represented by the action diagram shown in Figure 14.3.

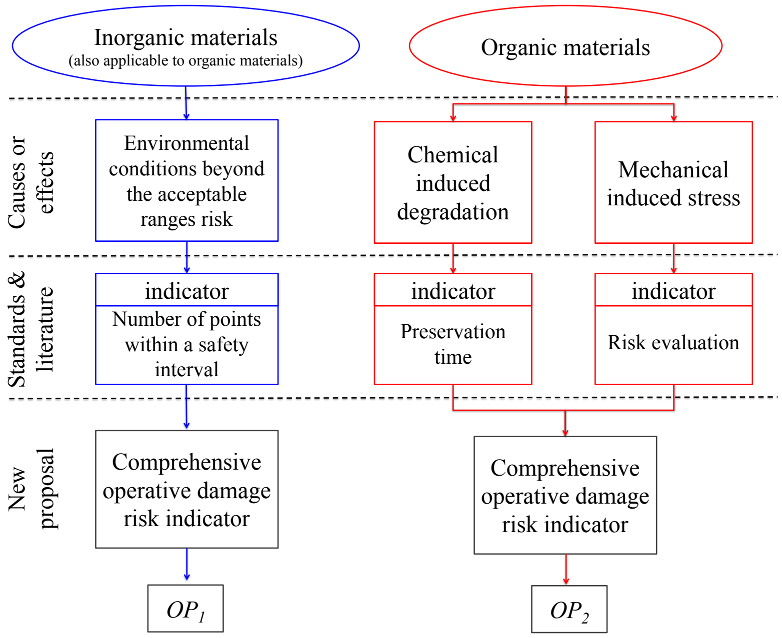

Figure 14.3. Logical scheme showing the proposed intervention approach.

Figure 14.3 shows, indeed, that the risk of damage could be estimated in three main ways, depending on the typology of the considered material. In particular, for both inorganic and organic materials the extent of the probable risk could be directly linked to monitored data of T and RH parameters (i.e. risk causes), by means of indicators related to recommended safety intervals. As for inorganic materials, other methods for the assessment of the probable risk of damage could be utilized; specifically, depending on the kind of damage analysed (i.e. risk effect), two types of indicators can be found in literature. The possible comprehensive operative damage risk indicator should therefore combine the above-cited different aspects, in order of suitably being used by curators in the contracts drafting with companies providing technical HVAC services for museums. Equation (14.4) shows, in fact, that the "overall damage risk" is given by a proper contribution of indoor parameters (i.e. T and RH) and damage effects induced to the work of art (i.e. chemical degradation and/or mechanical stress).

Such comprehensive and operational indicators *OP* might reasonably depend on indexes already used for assessing the appropriate indoor microclimatic conditions of museums.

14.3.2 Tools used for building-up the damage risk indicators

In the following sub-sections the above-cited indexes [25] will be described, attempting to estimate the probable damage risk in connection with assigned environmental conditions related to pre-set reference values, in order to select some of them for singling out the new proposed *OP* indicators.

14.3.2.1 Performance Index (PI)

The *Performance Index (PI)* is defined [26, 27] as the percentage of time during which a measured parameter lies within its recommended safety range. Specifically, *PI* is computed as the percentage of hours, for each month of a given year, in which the values of the considered measured parameters fall inside the ranges recommended by [18] and [28]. In particular, in the present work, only the T and RH physical parameters have been considered.

PI's most important feature is represented by the definition of microclimate "warning limits" (such as, indeed, T and RH) not to be exceeded, which should be set up also in accord with the curator knowledge and experience. For this reason, *PI* is often used to verify whether a museum's HVAC system was suitably designed in order to maintain the microclimatic conditions required for the preservation of the exhibited works of art, as suggest by the Italian Standard UNI 10829 [18] and the Italian Ministerial Decree [28, 29].

14.3.2.2 Preservation Index (IPI)

The Image Permanence Institute proposes a "Preservation Index" (*IPI*) [30], based on a detailed study of the hydrolysis cellulose acetate reaction, to be used as gauge of the combined effects that the indoor T and RH have on the exhibited works of art composed by organic materials.

The mathematical expression of the *IPI* (expressed in lifetime years), related to the kinetics reaction, is reported in equation (14.5).

$$IPI = \frac{e^{\frac{95220-134.9\times RH}{8.314\times T}+0.0284\times RH-28.023}}{365} \tag{14.5}$$

where T (°C) and RH (%) are, respectively, given assigned values of T and RH, supposed to remain constant and characterizing the considered environment.

14.3.2.3 Equilibrium Moisture Content (EMC)

The Equilibrium Moisture Content (*EMC*), expressed in percentage (%), can be defined as the moisture content reached at the equilibrium with the indoor environmental T and RH values [31]. The *EMC* has been used by the Image Permanence Institute in order to obtain information regarding the possible influence of such parameters (T and RH) on the risk of damage for the works of art.

Indeed, according to the *EMC* calculation method proposed by the IPI [32], environmental conditions are rated as "Good" or "Risk", based on the *EMC* values obtained from the monitored data of the T and RH parameters. In fact, the amount of moisture in the environment and the degree of fluctuation between periods of humidity and of dryness, are the factors, which promote mechanical (and/or physical) damage in vulnerable materials such as works of art (Table 14.1).

Table 14.1. "Mechanical damage" evaluation scales proposed by the Image Permanence Institute.

Mechanical damage		
Min % *EMC*	Max % *EMC*	RATE
> 5	< 12.5	Good
< 5	> 12.5	Risk

The expression for the calculation of the *EMC* parameter proposed by the Image Permanence Institute [33] is given by equation (14.6).

$$EMC = \frac{1800}{W} * \left(\frac{K\times H}{1-K\times H} + \frac{K_1\times K\times H + 2\times K_1\times K_2\times K^2\times H^2}{1+K_1\times K\times H + K_1\times K_2\times K^2\times H^2}\right) \tag{14.6}$$

where T represent the air temperature (°C), $H=RH/100$, with RH in (%) air relative humidity, and W, K, K_1, K_2 are the adsorption coefficients, that is:

$$W = 349 + 1.29 \times T + 0.0135 \times T^2 \tag{14.7}$$

$$K = 0.805 + 0.000736 \times T - 0.00000273 \times T^2 \quad (14.8)$$

$$K_1 = 6.27 - 0.00938 \times T - 0.000303 \times T^2 \quad (14.9)$$

$$K_2 = 1.91 - 0.0407 \times T - 0.000293 \times T^2 \quad (14.10)$$

14.4 Definition of two comprehensive operative damage risk indicators: OP_1 and OP_2

The literature indexes reported in section 3 are mainly used to assess whether the safety limits suggested for the environmental physical parameters of interest (in the present case, *T* and *RH*) are respected or not. They have not been specifically designed for taking into consideration the economic issues related to a possible damage risk condition, contrarily to what curators are often called to assess. Therefore, these literature indexes do not appear to be suitable enough tools to help curators in negotiating the stipulation of contracts with the “Global Service”.

Hence, on the basis of the above-mentioned considerations, and in reference to what previously outlined by the logical scheme of Figure 14.3, in the following the cases of inorganic and organic materials will be treated separately, in sight of singling out comprehensive operative damage risk indicators (OP_i) to be used by curators in their contract’s assessment:

$$OP_i = (function(PI) \mid function(IPI, EMC)) \quad (14.11)$$

14.4.1 An indicator designed for inorganic and organic materials: OP_1

As for both inorganic and organic materials, an effective indicator (OP_1) can be usefully derived on the base of the safety ranges existing in literature and reported in the UNI 10829 Standard [18]. This approach considers not only the percentage of time during which the measured physical parameters of the indoor environment fall outside the optimal range, but also the gap between these values and the limits of the considered range over that time. Such an approach thus allows the identification of the situations in which the artefacts are more exposed to risks when the HVAC system cannot be able to ensure the required microclimatic conditions.

Starting from the limits of the indoor physical parameters suggested by the UNI 10829 Standard [18], we propose here the building up of integrated parameters based on the evaluation of doses of *T* and/or *RH* released by the environment surrounding the artefact under study.

Following the logical process introduced in Section 14.3.1, with reference to equation (14.1) we initially define four damage risk functions (n = 4) characterized by four intervals of time. Specifically, Ns_1 is the number of intervals during which monitored indoor T fall below the lower limit; Ns_2 is the number of intervals during which monitored indoor T fall above the upper limit; Ns_3 is the number of intervals during which monitored indoor RH fall below the lower limit; Ns_4 is the number of intervals during which monitored indoor RH fall above the upper limit.

The first function takes into account only the intervals during which T values fall below the lower safety limit:

$$p_1(\tau) = \frac{|T(\tau) - T_{lim,lower}|}{|T_{lim,upper} - T_{lim,lower}|} \quad when\ T(\tau) < T_{lim,lower} \tag{14.12}$$

The second function, instead, takes into account only the intervals during which T shows values higher than the upper safety limit:

$$p_2(\tau) = \frac{|T(\tau) - T_{lim,upper}|}{|T_{lim,upper} - T_{lim,lower}|} \quad when\ T(\tau) > T_{lim,upper} \tag{14.13}$$

Similarly, it is possible to define two corresponding functions for the air RH:

$$p_3(\tau) = \frac{|RH(\tau) - RH_{lim,lower}|}{|RH_{lim,upper} - RH_{lim,lower}|} \quad when\ RH(\tau) < RH_{lim,lower} \tag{14.14}$$

$$p_4(\tau) = \frac{|RH(\tau) - RH_{lim,upper}|}{|RH_{lim,upper} - RH_{lim,lower}|} \quad when\ RH(\tau) > RH_{lim,upper} \tag{14.15}$$

Successively, with reference to equation (14.2), it is possible to define the “interval-related damage-risk” functions, that is:

$$f_{j,i} = \int_{\tau_{Bj,i}}^{\tau_{Ej,i}} p_j(\tau) \cdot d\tau \quad with\ \ i = 1 \dots Ns_j\ \ and\, j = 1 \dots 4 \tag{14.16}$$

Hence, referring to equation (14.3), the overall damage risk function can be put in the form:

$$g_j = \sum_{i=1}^{Ns_j} f_{j,i} \quad with\ \ j = 1 \dots 4 \tag{14.17}$$

Finally, the comprehensive operative damage risk indicator OP_1 can be defined as:

$$OP_1 = \sum_{j=1}^{4} \alpha_j \cdot g_j \tag{14.18}$$

where α_j are suitable weights, described in the following.

Hence, a total of four g functions are required to define the quality of the environment conditions (in terms of T and RH) related to HVAC system running interruption, which may be due to maintenance or unforeseen failure.

Based on their definitions, the g functions are used here to assess the operational indicator OP_1 depending on non-working periods of HVAC system, to be adopted by curators.

The α_j coefficients, reported in equation (14.18), are suitable weights relative to the T and RH parameters, representing the impact that the variations of these microclimatic parameters from the suggested ranges (i.e. ΔT and ΔRH) have on the works of art. In particular, it was here decided to distinguish such coefficients, based on their dependence on the specific parameter, as follows: $\alpha_1=\alpha_2= f(\Delta T)$ and $\alpha_3=\alpha_4=f(\Delta RH)$. These weighting coefficients could assume different values depending not only on the required microclimatic ranges for the work of art preservation, but also on the materials that compose a given artefact, and on its exhibition "history" in the considered halls. Hence, they must be established specifically for each one of them. In the present case it was proposed to use a scale of values (Figure 14.4) comprised between 0.2 (minimum impact) and 1 (maximum impact), based on the consideration that the narrower the safety interval, the more sensitive the artefact is to the considered microclimate parameter [34]. These values represent, at this stage, only a tentative proposal. Of course, their definition is up to curator, depending on his experience on the relationship between the work of art well-being and the indoor conditions of the exhibiting rooms.

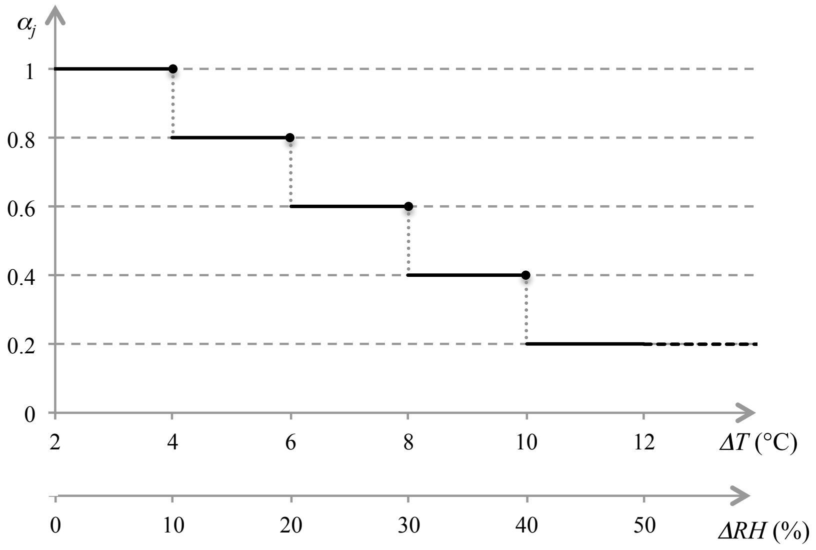

Figure 14.4. Proposed scale of values for the weighting coefficients based on the UNI10829 [34].

The structure of equations (14.16) and (14.17), except for the definition of the weighting parameters, is characterized by an important simplification, consisting in the implicit linearity assumption (i.e. a summation or integration) of the separate effects induced by *T* and *RH* (i.e. hypothesis of superposition of effects principle).

14.4.2 An indicator designed for only organic materials: *OP₂*

In the case of organic materials, it is proposed to implement the operational indicator OP_2 by assembling the *EMC* and *IPI* risk indexes thresholds proposed by the Image Permanence Institute [30, 32]. In particular, in order to take into account the degree of sensitivity of each of these two indexes with respect to the *T* and *RH* parameters it was chosen to build up the OP_2 indicator as follows.

Firstly, with reference to equation (14.1), we define only one ($n = 1$) "damage risk" function, which, referring to the instantaneous values of *T* and *RH,* considers when at least one of the two parameters fall outside of the safety range. That is:

$$p_1(\tau) = max\,[F(EMC(\tau)), G(IPI(\tau))] \qquad (14.19)$$

where *F* and *G* are assumed to be two proper logistic functions.

Subsequently, with reference to equation (14.2), the "interval damage risk" function can be defined in this case as:

$$f_{1,i} = \int_{\tau_{B1,i}}^{\tau_{E1,i}} p_1(\tau) \cdot d\tau \quad with\ i = 1 \dots Ns_1 \tag{14.20}$$

Referring to equation (14.3), the “overall damage risk” function (being only one damage risk in this context) can be put as follows:

$$g_1 = \sum_{i=1}^{Ns_1} f_{1,i} \tag{14.21}$$

Finally, for this particular case, the “comprehensive operative damage risk indicator” (*OP_2*) coincides with g_1, therefore:

$$OP_2 = g_1 \tag{14.22}$$

The functions *F(EMC)* and *G(IPI)* reported in equation (14.19) represent a combination of logistic functions and a logistic function respectively, relative to the *EMC* and *IPI* indexes, as reported in Figure 14.5.

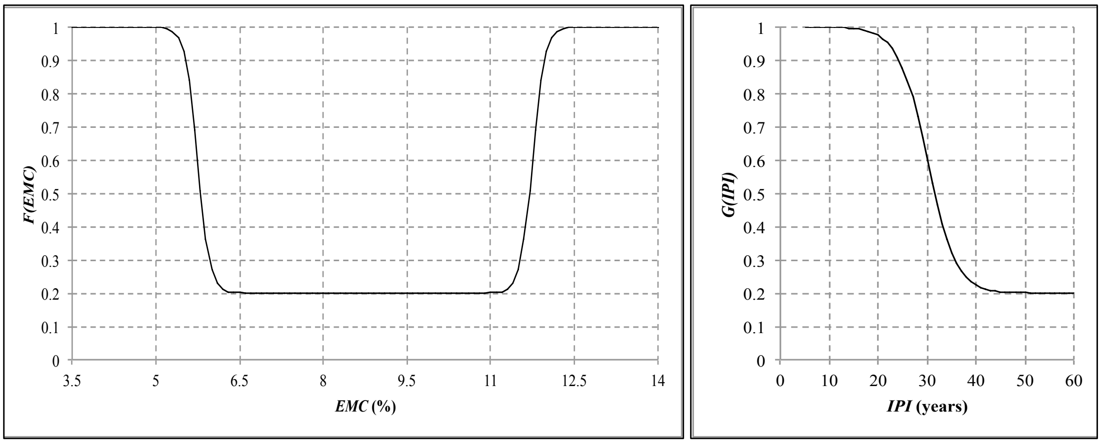

Figure 14.5. *F(EMC)* and *G(IPI)* behaviors.

It must be here underlined that, at this stage, some assumptions have been made on the *F(EMC)* and *G(IPI)* logistic functions, in particular it has been assumed that they return only values comprised between 0.2 (corresponding to a low risk level) and 1.0 (corresponding to a high-risk level). Also, regarding the risk evaluation scale relative to the *F(EMC)*, it was decided to assign a condition of “Risk” to values of the *EMC* index lower than 5 and higher than 12.5 (as suggested by the Image Permanence Institute [30, 32]), and a condition of “Alert” for the cases 5 < *EMC* index < 6.5 and

$11.0 < EMC$ index < 12.5; where these chosen limits of 6.5 and 11.0 approximately correspond to RH values of 35% and 60% respectively, considering a range of temperatures comprised between 5 and 35°C.

As for the risk evaluation scale relative to the $G(IPI)$, instead, the "Risk" condition has been associated to values of the IPI index lower than 10, while the "Alert" condition to $10 < IPI$ index < 50. In this case the chosen limit values of 10 and 50 are based on authors' considerations on a table (Table 14.1) reported in [30], namely supposing to consider a reference value of 50% for the RH and to assign the "Risk" and the "Alert" conditions to values of T of approximately 30°C and 20°C respectively.

14.5 Application of the two proposed *OP* indicators to a case study

The feasibility of the proposed methodology has been checked in the "Museo Regionale" of Palermo (Italy), located at *Palazzo Abatellis* (Figure 14.6), two halls of which – previously subjected to a monitoring campaign of the indoor physical parameters – have been considered for an example application of the OP_1 and OP_2 indicators, above defined.

Specifically, the works of art considered in the case study, shown in Figure 14.7, are the following:

- the *Virgin Annunciate* (dated 1476), placed in exhibition hall 10, a famous painting on wood by the Italian Renaissance artist Antonello da Messina.
- the *Triumph of Death* (dated 1446), placed in exhibition hall 2, one of the most representative frescoes of the late Gothic painting in Italy.

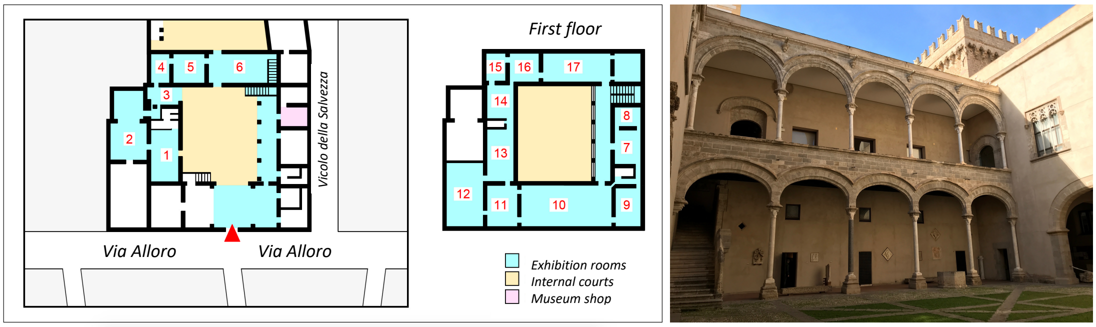

Figure 14.6. *Palazzo Abatellis*'s exhibition halls' layout (left) and internal atrium view (right).

Figure 14.7. *Triumph of Death* on the left, *Virgin Annunciate* on the right.

As for the recommended ranges of *T* and *RH* for these kinds of works of art, those suggested by the Italian standard UNI 10829 [18] and the Italian Ministerial Decree of 10 May 2001 [28] are the following:

- for the *Virgin Annunciate* (painting on wood): *T* comprised between 19°C and 24°C and *RH* comprised between 50% and 60%;
- for the *Triumph of Death* (fresco): *T* ranging from 10°C to 24°C and a *RH* varying between 55% and 65%.

The proposed approach preliminarily requires an analysis of the environmental conditions of the considered exhibition hall without the presence of the HVAC. This circumstance, corresponding to a HVAC system failure, in fact, represents free-floating conditions. In such situation the indoor parameters of *T* and *RH* may be obtained by a dynamic simulation or by a monitoring campaign. The latter, in this case, has been performed in the exhibition halls 2 (site of the *Triumph of Death*) and 10 (hosting the *Virgin Annunciate*) for a whole year.

For the sake of completeness, in order to show the seasonal variations of the climate characterizing the studied zone, in which the museum is located, the monthly trend of the mean values of external *T* and *RH* have been reported in Figure 14.8.

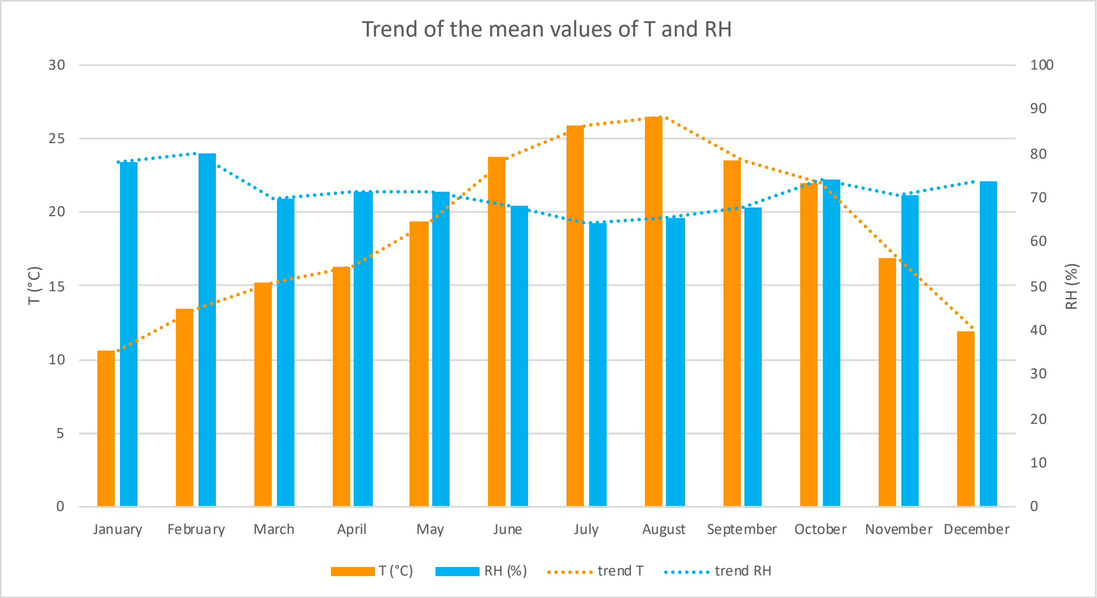

Figure 14.8. Monthly trend of the mean values of external *T* and *RH* monitored.

Further, for the assessment of the new OP_1 and OP_2 indicators, it has been hypothesized to install an ideal air conditioning system inside *Palazzo Abatellis*, able to maintain constant values of *T* and *RH* indoor parameters. In particular, for the indoor *T* a value equal to 21°C has been set for both the exhibition rooms hosting the two works of art; while the values of the *RH* in the two rooms have been set equal to the average of the limit values suggested by the legislation for the relative type of artwork exhibited, that is 55% for the *Virgin Annunciate* and 60% for the *Triumph of Death.*

14.6 Results

The simulations were carried out hypothesizing three different periods of interruption of the HVAC system for maintenance: 5, 15 and 30 consecutive days. A total number of 8760 simulations for each of the three scenarios were carried out, starting from the first hour of the first day of the year and postponing the service interruption of one hour each time. The corresponding simulation model has been implemented by means of the MATLAB™ environment.

In order to show the potential of each of the two new introduced indicators to be sensible to both *T* and *RH* parameters simultaneously, as a first step it was decided here to report a comparison among the complementary values of the index *PI(T-RH)*, and the indicators OP_1 and OP_2 relative to the 30 days interruption period. This choice relies on the fact that for such interruption period the differences between the results relative to the different indicators become more evident.

The results of the simulations were summarized by means of a monthly statistical graphical analysis, reported in Figure 14.9, using a boxplot visual representation for the obtained results.

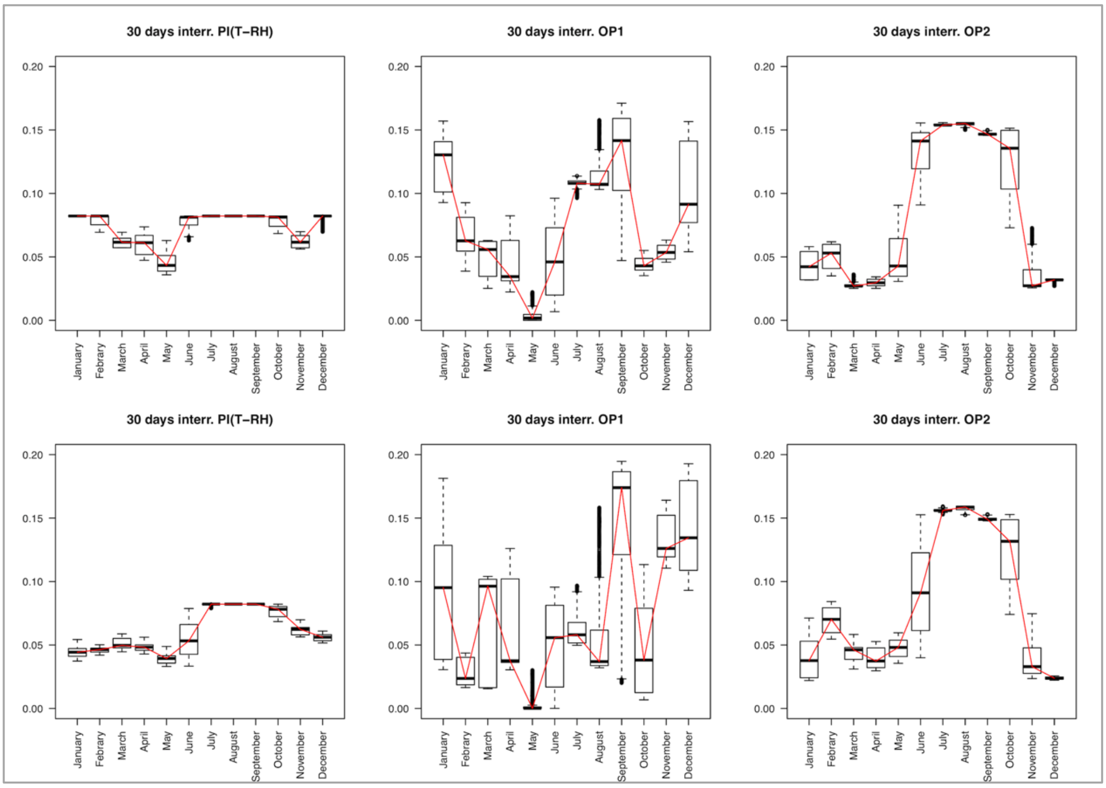

Figure 14.9. Comparison of the *PI(T-RH)*, *OP*$_1$ and *OP*$_2$ indicators, relative to the *Virgin Annunciate* "top" and the *Triumph of Death* "bottom" for the 30 days interruption period.

To allow the comparison among the index *PI* and the two *OP* indicators, it was decided to normalize the results obtained for each indicator using a scale of values comprised between 0 and 1. In this scale, "1" represents the highest level of damage risk (critical conditions) for the work of art, while "0" corresponds to the lowest level of damage risk (acceptable conditions). Specifically, the maximum and minimum values used to normalize the results are those relative to the case in which the HVAC system is not working for a whole year (i.e. free-floating conditions in the environment for the entire period), since the main purpose here is to compare the indicators among them, and not comparing their absolute values.

By observing Figure 14.9 it can be noted how the *PI(T-RH)* index shows a quite flat trend presenting only a very slight variations during summertime. Therefore, this index does not give very useful information.

As for the *OP*$_1$ indicator, this is the one that presents a wider variation as regards both the symmetry of the distribution and the dispersion of the values for both works of art.

The OP_2 indicator presents monthly trends similar to those of the OP_1 for both artefacts, although the dispersion of the values looks less accentuated, showing a possible critical period during the summer season.

We want here to underline that for the OP_1 simulations we considered an environmental physical parameters' data set rebuilt from the actual data monitored in free-floating conditions by means of a "response time constant" of approximately three days for the examined works of art [35]. Specifically, such "response time constant" is characteristic of the single works of art, and takes into consideration how the artefact reacts to the modality of variation of the physical parameters; that is, it considers the time necessary to have an appreciable relative variation of the artefacts' chemical and mechanical characteristics, in terms of degradation.

The results obtained for *PI(T-RH)*, OP_1 and OP_2, relative to the present case study, are reported in Figure 14.10, where *PI(T-RH)* appears to have a flattened trend with respect to OP_1 and OP_2, meaning that it does not seem to be very influenced by the seasonal variations.

The differences between *PI(T-RH)*, OP_1 and OP_2 observed in Figure 14.10 are ascribable to the intrinsic definition of the considered indicators. In fact, *PI(T-RH)* index does not consider the distance of the actual values from the suggested safety limits of the parameters T and RH.

On the contrary, the OP_1 indicator has been specifically built-up to evaluate the actual distance of the monitored values of the parameters T and RH from the relative safety ranges limits and it also considers the "response time constant" of the specific work of art. However, the fact that the choice of the weighting coefficients to be attributed to each work of art are up to the curator's decision represents a critical aspect, being such parameters crucial points in the definition of the indicator. The OP_2, finally, has been designed to have a strong dependence on the combined effects of both T and RH.

Graphs such those reported in the following Figure 14.10 allow curators to immediately identify the involved risks for each type of work of art, and for each period of interruption.

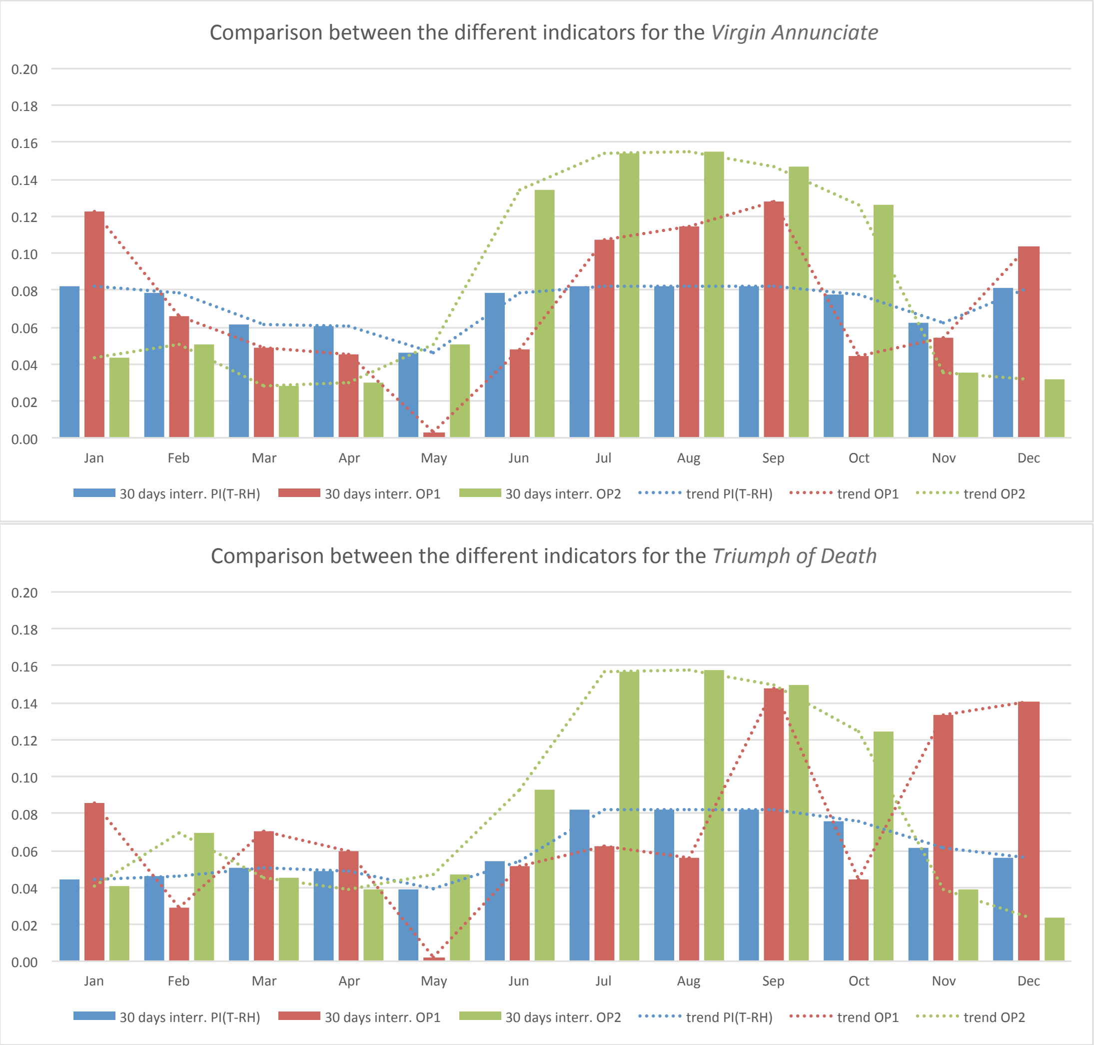

Figure 14.10. Comparison of the *PI(T-RH),* OP_1 and OP_2 indicators relative to the *Virgin Annunciate* “top” and to the *Triumph of Death* “bottom” for an interruption period of 30 days.

14.7 Discussions

The following two sub-sections respectively discuss the possibility of embedding economy-related considerations into the structure of the OP_i indicators, and the applicability of these indicators to other climate situations different from those of the analyzed site.

14.7.1 Embedding in the *OP* indicators economic-related factors

As previously mentioned, the proposed OP_1 and OP_2 indicators are meant to be adopted as decision-making tools to support curators in regulating the contracts with the companies responsible for the management of the HVAC systems (i.e. establishing the maximum time of acceptable disservice and evaluating the planned maintenance interruptions). For this purpose, in order to motivate the companies to solve possible HVAC failures in the shortest conceivable time, an *Economic Penalty (EP) function* could be included in the contracts, to be scaled according to the time of interruption of the system.

Assigning an economic penalty *EP* is not an easy task, since the economic value of a work of art is of difficult estimation (sometimes priceless); we suppose here to commensurate the economic penalty with the probability of occurrence of the HVAC failure and the consequent supposed amount of damage estimated for the work of art. In fact, the contractors should "pay the bill when they fail to respond to an emergency within the agreed-on time period" [23]. The tentative proposed relationship for the calculation of *EP* could assume the form indicated in equation (14.23):

$$EP = f(OP, P) \tag{14.23}$$

In equation (14.23) *OP* tries to take into account the technological/engineering aspect of the problem by integrating the physical indoor parameters, the probability of failure occurrence of the HVAC system, and a time-related parameter. *P* should consider the economic aspect, representing an estimate of the amount of damage related to the work of art (or to the whole museum), for which determination the curator's (stakeholders) support/expertise is fundamental.

As an example, Table 14.2 contains the values of *EP* for the works of art considered in the case study presented here, and calculated as a product of OP_2 and P (that is, $EP = OP_2 \times P$), assuming to assign to *P* a tentative value of 1000 €/day. This totally fictitious value is simply aimed at making a comparison among the different relevancies that the occurrence of the hypothesized interruption period in the different months of the year could have on the contracts.

Table 14.2. Tentative *EP* evaluation for the considered case study, applied to the *Virgin Annunciate*.

Values of $EP = f(OP_2, P)$ – expressed in **€/day** – applied to the ***Virgin Annunciate***													
	Month in which the interruption occurs	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Interruption period	1 – 5 days	7.28	8.53	4.46	4.71	7.52	23.51	25.64	25.95	24.31	22.32	4.37	5.36
	6 – 15 days	21.58	25.66	13.57	14.51	23.41	69.25	76.92	77.78	73.12	65.83	14.18	16.05
	16 – 30 days	43.56	50.27	28.08	29.69	50.13	134.03	154.20	154.59	147.02	125.73	34.94	31.52

14.7.2 About the extensibility of the obtained results to different climatic conditions

It must be specified that the results obtained in the presented case study are based on the monitoring of *T* and *RH,* in free-floating conditions, performed for a whole year in the halls housing the two works of art. This represents a peculiar case, since such indoor monitored data are not usually available. In order to consider the aspects related to climate characterizing the site where the museum is located, a possible further step is represented by the implementation, in a dynamic simulation model, of a function linking the outdoor monitored data with the indoor microclimate conditions, by considering the thermal inertia of the building. In particular, the indoor microclimatic conditions could be approximately obtained from the external climatic data assuming certain values of thermal capacity and thermal resistance for the building components.

14.8 Conclusion

The present work started from considerations regarding the comparison of some currently available Standards and indexes for the implementation of two comprehensive operative damage risk indicators (OP_1 and OP_2 here introduced) able to provide an evaluation of the microclimate related risk for works of art, in order to help museums curators in stipulating contracts with HVAC maintenance and management companies, by also considering the economic aspects. Furthermore, these indicators could also be suitable for planning the management and maintenance procedures of museums' HVAC systems.

The feasibility of the OP_1 and OP_2 has been here checked by means of an example application involving the "Museo Regionale" of Palermo (Italy).

Results showed that, contrary to what is provided by *PI(T-RH)*, indicators OP_1 and OP_2, make it possible to detect the most critical periods for the works of art, since they are able to account for both seasonal variations and the combined effects of *T* and *RH*. As an example, by analyzing the results related to the *Virgin Annunciate* it is possible to note how the new indicators OP_1 and OP_2 present maximum and minimum values that differ from each other by at least one order of magnitude: $OP_{1,max}$ = 0.13 in September and $OP_{1,min}$ = 0.003 in May; $OP_{2,max}$ = 0.15 in August and $OP_{2,min}$ = 0.03 in March. While the same cannot be said with regard to *PI(T-RH)*; in fact, $PI(T\text{-}RH)_{max}$ = 0.08 in September and $PI(T\text{-}RH)_{min}$ = 0.04 in May.

The case study carried out via such application showed that further investigations must be conducted. In particular, adequate attention must be paid to the influence that both the climate zone in which the museum is sited and the season of the year in which the HVAC disservice occurs have on the physical parameters (*T* and the *RH*) variations. Moreover, the aspect regarding the link between the different types of works of art that can be present in a museum, and/or their simultaneous presence within the same exhibition hall, should also be further explored. As regards, instead, the economic aspects, it must be highlighted the difficulty in quantifying the damage risk related to the artefacts, due to the difficulty in assessing a proper monetary value for certain particular types of works of art, and also to the appropriate form that the relationship for the calculation of *EP* should assume.

In conclusion, the cooperation between curators, technicians and researchers working on the assessment of the *OP* indicators is essential for future development in this field of study.

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SECTION III.A – Results and Findings

The principal key points emerged from the study illustrated in this section, regarding the implementation of two new operative risk indicators as tools for negotiating contracts between curators of Museums and HVAC technical services providers, are:

- contrary to the existing *PI(T-RH)*, the new proposed indicators OP_1 and OP_2, make it possible to detect the most critical conditions for the works of art, since they are able to account for both seasonal variations and the combined effects of *T* and *RH*;
- graphical representations of the results (such those reported in Figure 14.10) allow curators to immediately identify the involved risks for each type of work of art, and for each period of interruption of the HVAC system;
- in order to motivate the companies to solve possible HVAC failures in the shortest conceivable time, an *Economic Penalty (EP) function* could be included in the contracts, to be scaled according to the time of interruption of the system and the values of the work of arts.

PART III – Tertiary Buildings: Historical and Tourism

SECTION III.B – Tourism Buildings: Energy Savings and Quality Brands

As for the previous one, in this section specific attention was given to another kind of structure notable in the Italian building panorama, namely tourism buildings, in particular the historical ones hosting agritourisms. The agritourist sector represents indeed an important economic driver in Italy characterized by persistent growing trend in recent years.

Thus, in light of the current EU directives and environmental excellence brand and of the National guidelines concerning the achievable environmental improvements consequent to the implementation of some energy efficiency interventions, this section reports the application of an analysis methodology aimed at assessing the possible improvements obtainable by a given agritourism when implementing such specific energy efficiency measures.

This section of the dissertation comprises one chapter:

Chapter 15 - Towards Nearly Zero Energy and Environmentally Sustainble Agritourisms: The effectiveness of the Application of the European Ecolabel Brand

Chapter 15 - Towards Nearly Zero Energy and Environmentally Sustainable Agritourisms: The Effectiveness of the Application of the European Ecolabel Brand

This chapter consists in the following journal paper:
Cirrincione, L., Gennusa, M.L., Peri, G., Rizzo, G., Scaccianoce, G., Towards nearly zero energy and environmentally sustainable agritourisms: The effectiveness of the application of the European ecolabel brand, (2020) Applied Sciences (Switzerland), 10 (17), art. no. 5741.
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Abstract: Tourism represents an important economic driver in Italy, being responsible for approximately 13.2% of the total GDP (a value higher than the reference European average) and for nearly 10% of the regional GDP. Among the touristic sectors, the agritourist ones show a persistent growth, experiencing in 2019 a 6.7 point percentage improvement compared to the 2017 figures. Given this situation, the transition towards a low-carbon path, affecting the building sector for some time, should also involve agritourist buildings, through the release of EU directives, member state laws, and technical rules. On the other hand, agritourism sites could be awarded the Community EU Ecolabel. Unfortunately, awarding the EU environmental excellence brand implies the availability of several data on building energy behavior that should then be managed by complex evaluation tools. To overcome this issue, the use of the simplified ARERA (Italian Regulatory Authority for Energy Networks and Environment) technical datasheets, issued to assess environmental improvements consequent to energy efficiency interventions in the urban residential building stock, is proposed. The application of this tool totally avoids using building computer-based simulation models, thus facilitating the preparation of the EU Ecolabel request documentation by agritourism owners. Being awarded the Community EU Ecolabel also implies approaching a net zero energy condition because of a lower energy consumption and a minor recourse to fossil fuels. For this purpose, an application of an easy graphical method, previously developed for residential and commercial buildings, which visually represents improvements achievable by a given agritourism when implementing energy efficiency measures, is presented.

Keywords: building energy efficiency; European environmental brands; tourism sector; agritourism; nearly zero energy buildings (nZEB).

15.1 Introduction

Tourism, and the activities connected to it, represent an important sector of the economic system. According to recent statistics the tourism industry represents about 10% of total global gross domestic product (GDP) and 7% of global trade [1,2], accounting for approximately 11% of the world's employment, with an expected positive economic growth trend [3,4]. Tourism constitutes a significant contributor to energy consumption, both at a global and European scale [5–7], which translates to a significant impact on the environment and ecosystem; it is in fact responsible for about 5% of the global CO_2 emitted by human activities [1,8].

Accommodation (thus the building), in particular, is the third energy consuming item (after travel and transport), much of which is consumed in space heating or air conditioning (up to 50% in some cases), followed by hot water, and cooking [9,10]. Moreover, a study conducted by the World Tourism Organization and the United Nations Environment Programme [11] estimates that accommodation generates 21% of tourism's total greenhouse gas (GHG) emissions. Accordingly, the number of papers analyzing tourism significance, in terms of energy consumption [12,13] and impacts on emissions [14,15], has been increasing lately.

Consequently, in recent years much attention has been paid to the concept of sustainable tourism, which in accordance with the United Nations Environment Programme (UNEP) and the United Nations World Tourism Organization (UNTWO) is defined as "development of tourism activities with a suitable balance between the dimensions of environmental, economic, and sociocultural aspects to guarantee its long-term sustainability". Hence, the challenge of sustainable tourism is to mitigate its negative impacts, consisting mainly in: (i) high energy consumption, (ii) increasing GHG emissions in the atmosphere, and (iii) the contribution to climate change [16].

Therefore, taking into consideration global [17,18], European [19–22], and national [23] policies, the UNWTO recommended three central actions on which the tourism sector should concentrate in order to contribute in achieving a more sustainable development [1,24], which are resource efficiency, environmental protection, and climate change (linked to sustainable development goals (SDGs) 6, 7, 8, 11, 12, 13, 14, and 15) [25].

At the European scale, the European Commission set the basis for the best environmental management practice in the tourism sector in accordance with Article 46 of the Eco-Management and Audit Scheme (EMAS) regulation [26,27]. Furthermore, by means of the "Guide on EU funding for the tourism sector 2014–2020" [28] the EU states that effective governance, policies, frameworks, and tools need to be implemented in order to properly guide and support (also from an economic point of view) the development and promotion of sustainable tourism practices.

Tools like these are indeed important because they encourage the owners and/or managers of the accommodation facilities to use practices and systems that allow both energy savings and pollutant emissions, by favoring the visibility of these structures in terms of environmental sustainability, which represent an added value, given that tourists are becoming increasingly more attentive to this issue.

In this regard one of the first initiatives undertaken by the European Community has been the releasing of the EU Ecolabel for tourist accommodation services [29], created to improve the environmental performance of hotels, campsites, hostels, agritourisms, holiday homes, and bed & breakfasts, by providing efficient guidelines on the action to be implemented in order to lower their environmental impact; and which still remains one of the most implemented initiatives.

The promotion of sustainable tourism is also the basis of the nearly zero-energy hotels (neZEH) project, launched by the Intelligent Energy Europe Programme of the European Commission, with the intent of supporting European hotels in complying with the nZEB (nearly-Zero Energy Buildings) regulations [1]. On this subject, various studies have been conducted aimed at analyzing the achievable energy saving measures [30–32] and proposing suitable strategies and policies to be adopted [33,34].

Looking at the national scenario, the tourism issue is particularly relevant, considering that 16.5% of EU accommodation facilities are located in Italy [35], and since in the last two years Italy resulted to be amongst the top five most visited European tourist destinations (for accommodation in hospitality facilities), with a 13.4% share of the total of the EU-28 [36,37].

According to some recent statistics, the Italian tourism sector represents 13.2% of the national GDP (for a total contribution of around 230 billion euros), higher than both the world and European figures (which stand at around 10%). The economic impact of tourism is significantly reflected in the job market, accounting for 14.9% of the country’s total employment [38]. Tourism is in fact one of the fastest growing industrys in Italy, and both public and private business organizations are strongly interested in its economic and environmental impact, both at national and regional level [39,40].

Thus, from the collaboration between such organizations and the national and regional governments, different initiatives have been undertaken from an environmental sustainability point of view in recent years. These include the creation of a set of national environmental quality certifications (besides the previously cited EU Ecolabel), including the “Green Key” [41], “Bandiera Blu” [42], and “Spighe Verdi” [43], born from the collaboration between the Italian Foundation for

Environmental Education—FEE Italia (whose actions are supported by ONU, UNEP, UNWTO, and UNESCO) and national authorities dealing with environmental policies [44].

Furthermore, other economic initiatives have been implemented to encourage the use of sustainable energy solutions through financial incentives. The “Tax Credit Alberghi—Bonus alberghi e agriturismi” (bonus for hotels and agritourism), a tax facility that encourages various upgrading activities, including those aimed at improving energy efficiency, has recently been introduced, specifically for accommodation facilities [45].

Agritourism, or rural tourism, has been promoted as a practice able to encourage the use of green practices, making farms sustainable and also maintaining the local historical and natural settings [8,46].

Thanks to this, according to recent statistics in Italy, the agritourism sector continues to record a growing trend, both in the number of structures, and in the presence of customers and its economic value. Agriculture economic reports make it possible to measure the economic dimension of the agritourism sector, which is equal to 1.36 billion euros, up 6.7% compared to the previous year. In particular, 60% of agritourisms are located in the regions of central and southern Italy, where Sicily prevails with more than 600 farms [47].

The growing interest in the agritourism sector is also reflected in the academic world, where studies concerning both the economic and social benefits of various tourist activities in the rural area, including agritourism [48], and the environmental performance of agritourism companies in terms of energy performance [49,50], can be found.

In the present work we verified whether the simplified ARERA (Italian Regulatory Authority for Energy Networks and Environment) technical datasheets [51], issued for the urban residential building stock, can be easily applied to estimate the increase in energy efficiency (or the corresponding decrease in the release of polluting substances) consequent to the adoption of some improvements to a building or plant, planned for the issuance of the EU Ecolabel brand for accommodation facilities [29]. The convenience in the use of these technical datasheets lies in the fact that they allow the estimation of the energy demand reductions without necessarily going through the building simulation. For this purpose, a case study has been conducted to estimate what advantages agritourism owners could gain in adopting a well-known brand such as the EU Ecolabel [29], with particular reference to the actions aimed at saving energy and reducing emissions of pollutants, from the perspective of a possible “nearly Zero Energy Agritourism (nZEA)”, in parallel with the previously cited nZEB and neZEH projects.

The idea at the base of this work stems from the numerical consistency of agritourisms in Sicily [47] and their conceivable growth trend, which is a consequence of the increased interest in the rural landscape of the territory and in the products of the land that are strongly orienting tourism, directing it not only towards the urban context. The adoption of an environmental certificate like the EU Ecolabel [29] can therefore represent an advantage both for agritourism owners and for the entire territory.

Furthermore, the owners of agritourism in Sicily can apply for subsidized loans and financial funding [28,52] in the regional area and beyond. However, such requests must be supported by information concerning the consumption and energy efficiency of the agritourism and, in line with the new European directives on sustainability [17–19], by information on the environmental performance of the buildings themselves (premises).

Normally this information is of a complex nature and tends to imply the use of sophisticated simulation models, the use of which is not always the prerogative of (or available to) the managers of the holiday farms. The same problem can be found by analyzing the work of the decision makers who have to assess the adequacy of the requests for funding.

Essentially, the availability of simple but reliable tools for evaluating these premises is of paramount importance for the orientation of this important tourism sector towards a sustainable path.

Hence, as previously mentioned, in order to provide a contribution to this important issue we assessed the reliability of a scheme of simple computational methods provided by the Italian Regulatory Authority for Energy Networks and Environment—ARERA [51], specifically for the residential and tertiary building stock. The advantage in the use of this computational scheme lies indeed in the fact that it is based on excel spreadsheets (technical datasheets) which, as already mentioned, allow the estimation of the energy demand reductions without the need of simulating the building behavior.

15.2 Materials and methods

The proposed methodology aims at considering together in an easy and accessible way two aspects of the sustainability, which are energy efficiency and environmental safety, in order to help agritourism owners, and/or managers, to make decisions that are more favorable to them and consistent with the European policies in force. Specifically, according to the presented approach, the selection of energy efficiency interventions is based on a combination of the ARERA technical datasheets and the EU Ecolabel criteria, hence taking into account the environmental sustainability aspects, and also in view of achieving a possible nearly zero energy condition (nZEA). Therefore, two Sicilian agritourisms have been selected to show how the application of the proposed methodology actually works.

The considered approach can also be seen as a simple diagnosis method aimed at facilitating the social appropriation of knowledge and technology, so that the owners of agritourism facilities can confidently check their level of eco-efficiency. Moreover, the method can be utilized in order to choose between addressing actions concerning the energy performance of the structure or interventions regarding the installation of new (renewable) energy plants.

15.2.1 Agritourism Definition

The Italian national legislation [53], and the regional Sicilian one [54,55], define as ‘agritourism’ activities, those reception and hospitality activities exercised by agricultural entrepreneurs, through the use of their own company connected with the activities of cultivation of the land, forestry, and animal breeding. Thus, agritourism activities include:

- providing accommodation;
- administering meals and beverages consisting mainly in products of their own production and products from farms in the local area;
- organizing recreational, cultural, educational, sports, and excursion activities aimed at promoting and supporting the territory and the rural heritage.

15.2.2 The ARERA Technical Datasheets

In the present work, the use of ARERA technical datasheets [51] was not an arbitrary (random) choice, but it was decided to turn to these methods since, although simplified, they constitute an official reference at the Italian national level.

The Italian Regulatory Authority for Energy Networks and Environment—ARERA is indeed an independent body, established with the task of protecting consumers’ interests and promoting competition, efficiency, and the spread of services, and having adequate quality levels, through regulation and control activities. The action of ARERA concerns the sectors of electricity and natural gas [56], water services [57], district heating and district cooling [58], and the waste cycle [59].

One of the main tasks of ARERA is to promote the rational use of energy, with particular reference to the promotion and diffusion of end use energy efficiency and/or energy saving actions, and the adoption of measures for sustainable development. Among the feasible actions, there are both active measures, which involve the installation of high efficiency equipment, or the insertion of regulation devices for a more efficient use of energy, and passive interventions such as the modification of buildings' envelope in order to reduce losses.

In this regard, the technical datasheets proposed by ARERA establish the guidelines for the preparation, execution, and final evaluation of specific actions, aimed at increasing energy efficiency (or promoting energy saving), providing reduced rates of primary energy consumption actually achieved (expressed in toe—Tons of oil equivalent), and also for the purpose of issuing energy efficiency certificates. Table 15.A1 in Appendix 14.A reports a comprehensive list of the current standardized and analytical ARERA technical datasheets.

15.2.3 The EU Ecolabel Brand

Established in 1992 (by Regulation n. 880/92 [60], now disciplined by Regulation (EC) n. 66/2010 [61] in force in the EU-28) and recognized across Europe and worldwide (Figure 15.1), the EU Ecolabel is a voluntary environmental performance certificate that is awarded to products and services meeting high environmental standards. The EU Ecolabel encourages companies to develop products and provide services that consume less energy, and generate less waste and CO2 emissions. As of March 2019, an increase by 88%, with respect to 2016, of the number of EU Ecolabelled products/services has been registered. Leading countries for number of products/services are: Spain, Italy, Germany, Belgium, and France [62].

Figure 15.1. Official EU Ecolabel logo [62].

The EU Ecolabel provides exigent criteria, and relative guidelines, depending on the type of product and/or service, in order to reduce their overall environmental impact. Such criteria are established at a European scale with a wide participation of interested parties, including both public authorities, and consumer and environmental associations [63].

In particular, the EU Ecolabel for tourist accommodation services [29] was created specifically for hotels, campsites, hostels, agritourisms, holiday homes, and bed & breakfasts, in order to improve their environmental performance, by providing a set of criteria on the action to be implemented in order to lower their impact. Such criteria are divided into mandatory and optional, and focus on the five categories;

general management, energy, water, waste and wastewater, and other, as shown in Table 15.A2 in Appendix 14.A.

In order to be awarded the EU Ecolabel a tourist accommodation service, other than falling within the product group “tourist accommodation” according to the legal obligations of the country in which the accommodation is located, must comply with all the mandatory criteria (if applicable), and receive at least twenty points under the optional criteria [29].

An added value, in terms of visibility, for tourist accommodation owners lies in the fact that the EU Ecolabel is recognized by the majority of travelers as a way of legitimizing the accommodation’s claims that it is making real efforts to reduce its impact on the environment in its operational activities.

15.2.4 Analysis Methodology

15.2.4.1 Merging the ARERA Technical Datasheets and the EU Ecolabel Criteria

As mentioned in the introduction section, the aim of the present work is to verify whether the simplified ARERA technical datasheets can be applied to estimate the increase in energy efficiency consequent to the adoption of some actions planned for the issuance of a EU Ecolabel for Tourist Accommodation Services, without necessarily going through the building simulation. Obviously, an increase in the energy efficiency implies a corresponding decrease in the release of polluting substances.

Therefore, since this work is mainly focused on the energy criteria, starting from the assumption that the considered agritourism meets all the mandatory criteria, it was decided to analyze possible “environmental action packages”, consisting of different combinations of the actions established by the optional energy criteria, which are better suited to a scenario such as agritourism, and which allow the obtaining of the weight of the energy category on the twenty points minimum limit set by the regulation, which corresponds to 7.34 points.

To this purpose, only the ARERA datasheets regarding the actions related to the improvement of the structure energy efficiency that could be transferred and applied to agritourism structures, according to the EU Ecolabel for Tourist Accommodation energy criteria, have been considered, as reported in Table 15.1, where the correspondent energy consumption categories have also been reported.

Table 15.1. Correspondence between the Italian Regulatory Authority for Energy Networks and Environment (ARERA) datasheets and the EU Ecolabel energy criteria.

ARERA Technical Data Sheet N.	EU Ecolabel Criterion N.	EU Ecolabel Achievable Points	Energy Consumption Category [1]
5	33	4	HVAC
7	39, 40, 41	3.5	RES
8T	6	2	DHW
15T	6, 7	1.5	HVAC
19T	7	3.5	HVAC
27T	6	1.5	DHW
6	-	-	HVAC
20T	-	-	

[1] HVAC—Heating, Ventilation, and Air Conditioning; DHW—Domestic Hot Water; RES—Renewable Energy Source.

As can be seen in Table 15.1, the two ARERA datasheets 6T and 20T, additional to those that can be associated to the EU Ecolabel, have also been taken into account. In fact, even though these two intervention typologies are not foreseen by the current Ecolabel scheme, they represent actions that can actually be applied to an agritourism structure in the perspective of a possible “nearly Zero Energy Agritourism (nZEA)” as a parallel with the well-known nZEB concept; and also, in view of a possible future improvement of the Ecolabel scheme.

The selected datasheets (Table 15.1), have been then put into the form of appropriate excel spreadsheets.

The equations relative to the ARERA calculation procedures, for each considered technical datasheet, are given in Appendix B.

One aspect that must be highlighted here regards the fact that while datasheets 5, 6, 15T, 19T, 20T, and 27T enable obtaining savings of consumed energy (energy saving measures, ESM), datasheets 7 and 8T allow, instead, the production of energy from renewable sources (renewable energy sources, RES).

15.2.4.2 Methodology Application Feasibility

With the aim of assessing the potential energy savings, with reference to a real context, it was decided to select two agritourisms situated in the Sicilian province of Palermo, considered as representative of the whole regional agritourism context regarding the size, the provided services, and more importantly for the purpose of the proposed methodology object of the present work, in terms of energy consumption. Apart from these physical and energy features, both agritourisms were selected thanks to their wide offer of services, which are representative of these kind of farms, and due to the fact that they operate in the two climatic zones where agritourisms are mainly sited in Sicily. Specifically, the two agritourism are *Villa Dafne*, sited in Alia and belonging to climatic zone D, and *Bergi*, located in Castelbuono and classified as climatic zone C. Both agritourisms fall into solar belt 3. Table 15.2 describes the main general characteristics of the two structures.

Table 15.2. General characteristics of the two selected agritourisms.

Characteristic	***Villa Dafne***	***Bergi***
Covered surface (m^2)	1000	1400
Glazed surface (m^2)	236	305
Opaque surface (m^2)	2768.5	2791.75
Surface/Volume ratio (-)	0.62	0.5
N. of seats in the dining area	150	180
N. of rooms	35	34

In Table 15.3 is reported the information relative to the energy characteristics of interest for the conducted study, which were obtained by on field surveys and interviews with the owners of the two businesses, thanks to which it was possible to reconstruct the energy consumption relative to an entire year of operation of the structures. In particular, the data regarding the energy consumption were distributed between four main categories and accordingly broken down into percentages, and corresponding toe/year, also with reference to the corresponding energy sources. As for the energy sources’ average costs, the following values were used:

- 0.19 €/kWh for electricity;
- 1.17 €/Sm^3 for natural gas;
- 0.90 €/lt. for diesel oil.

Table 15.3. Energy sources and energy consumption breakdown for the two selected agritourisms.

Category	**Source**	***Villa Dafne***		***Bergi***	
		%	**Toe/Year**	**%**	**Toe/Year**
Domestic Hot Water (DHW)	natural gas/diesel oil	0	0.00	16	5.09
	electricity	22	9.72	6	1.91
Lighting	electricity	15	6.63	15	4.77
Heating, Ventilation and Air Conditioning (HVAC)	natural gas/diesel oil	25	11.05	15	4.77
	electricity	14	6.19	24	7.64
Other	natural gas/diesel oil	0	0.00	0	0.00
	electricity	24	10.60	24	7.64
	Total		**44.18**		**31.82**

Subsequently, it was hence possible to obtain the achievable energy savings (*AES*), in terms of percentage of electricity consumption covered by the datasheets proposed interventions on an annual basis, by comparing the values obtained from Equations (15.A1) to (15.A8), and the total energy consumption (Table 15.3), by means of the following equation:

$$AES_i = \frac{R_i}{Tot.\ cons._j}\ [\%] \tag{15.1}$$

where:

- R_i represent the energy savings obtained from Equations (15.B1) to (15.B8);
- $Tot.\ cons._j$ is the total figure reported in Table 15.3;
- i and j represent the selected intervention and the considered agritourism, respectively.

Regarding the pollutant emissions, an assessment of the CO_2 emissions' reduction was conducted assuming for the considered climatic context an emission factor equal to 2.30 tCO_2eq/toe for the electrical supply [64,65], while for natural gas and diesel oil an emission factor of 3.08 tCO_2eq/toe and 2.34 tCO_2eq/toe, respectively [66].

In order to single out the most convenient aforementioned "environmental actions packages", an economic estimation relative to the interventions suggested by the ARERA technical datasheets was also performed. To this purpose, the information relative to the costs of supply and installation for the materials, used to calculate the proposed interventions costs, were obtained from the current regional price list [67] and from local market surveys, as reported in Table 15.4.

Table 15.4. ARERA technical datasheets proposed interventions costs.

Datasheet N°	Proposed Inttervention	Cost
5	Replacement of simple glazing with double glazing	407.13 €/m^2
7	Use of photovoltaic systems with an electrical power of less than 20 kW	1898.42 €/kWp
8T	Installation of solar collectors for the production of domestic hot water	578.73 €/m^2
15T	Installation of outdoor air electric heat pumps instead of boilers in newly built or renovated residential buildings	4901.323 €/UFR*
19T	Installation of high efficiency outdoor air conditioners with cooling capacity lower than 12 kWf	490.13 €/kW
27T	Installation of electric heat pump for domestic hot water production in new and existing plants	570.65 €/UFR
6	Wall and roof insulation	29.32 €/m^2
20T	Thermal insulation of walls and roofs for summer cooling in domestic and service sectors	29.32 €/m^2

*UFR - reference physical unit

Successively, the economic savings, in terms of saved €/year, were obtained by multiplying the energy savings with the energy sources' average costs, according to the considered categories breakdown (Table 15.1). Furthermore, in order to select the optimal "environmental actions packages", for these the pay-back periods (not discounted) were also calculated and expressed in years.

15.3 Results

In this section the outcomes of the application of analysis methodology are reported.

Regarding the input parameters used in the equations relative to the ARERA calculation procedures, for each considered technical datasheets, these are given in Table 15.B1 in Appendix 15.B.

The following Figures 15.2 and 15.3 show the achievable energy savings (*AES*) on the total annual consumption, relative to the application of the intervention proposed by each considered ARERA datasheet, to the two agritourisms. On the right side of the graphs, the EU Ecolabel points corresponding to each datasheet are also reported.

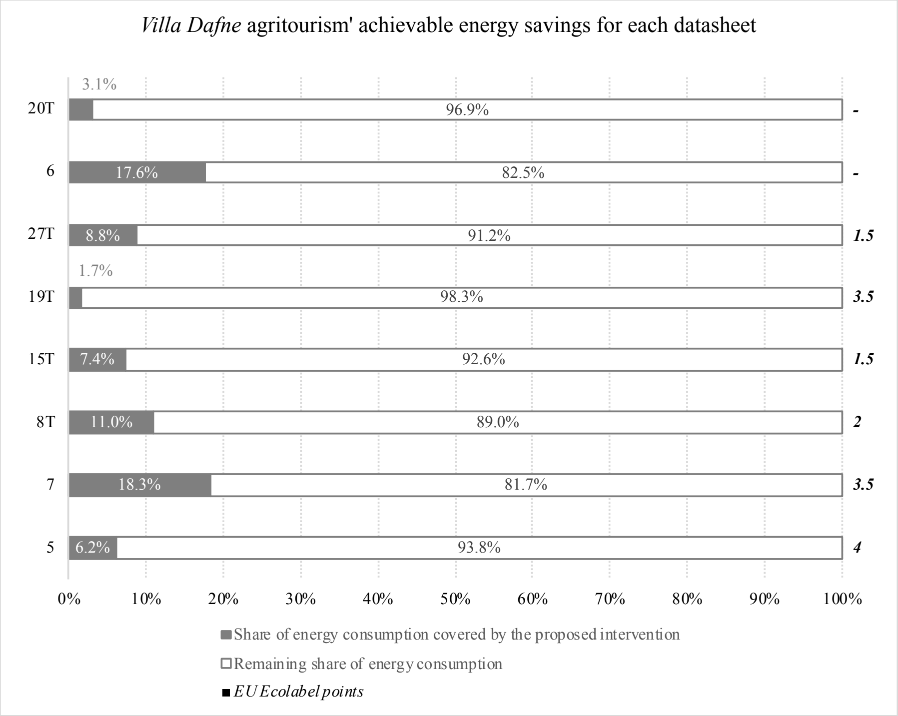

Figure 15.2. Achievable energy savings (*AES*), on an annual basis, and EU Ecolabel points relative to each considered ARERA datasheet for *Villa Dafne* agritourism.

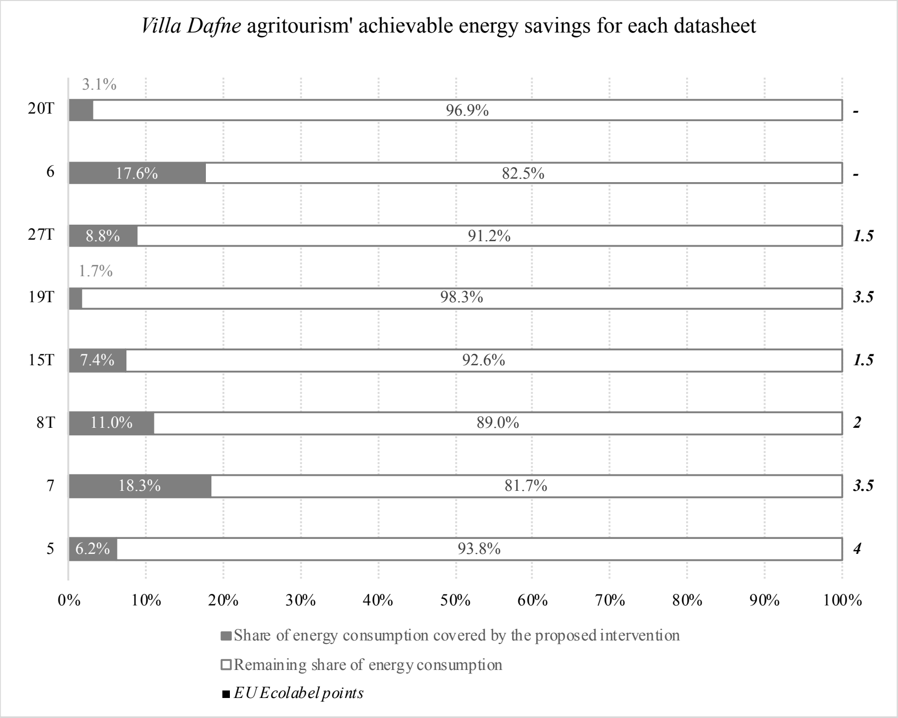

Figure 15.3. Achievable energy savings (*AES*), on an annual basis, and EU Ecolabel points relative to each considered ARERA datasheet for *Bergi* agritourism.

Figures 15.2 and 15.3 show how, amongst the ARERA proposed interventions enabling the obtaining of an EU Ecolabel score, the implementation of a photovoltaic (PV) system (datasheet 7) would be the one allowing the gain of a greater advantage in terms of energy consumption. Concerning the savings related to the domestic hot water (DHW) category, by comparing datasheets 8T and 27T, which are alternatives to each other, it can be observed how 8T would be the more convenient choice. Regarding the heating, ventilation, and air conditioning (HVAC) category, the savings achievable through the application of datasheets 15T and 19T should, instead, be considered jointly (15T + 19T) as they can be attributed to the same improvement intervention. As for datasheet 5, although it represents one of the easiest measures to implement, it does not seem to bring the benefits that would have been expected.

With respect to datasheets 6 and 20T, also in this case the consideration that the attainable benefits must be considered together (6 + 20T) is valid. As already explained these two datasheets fall out of the Ecolabel scoring scheme, nevertheless they represent the second-best intervention that allows the highest energy savings, after datasheet 7.

The overall obtained results for the two considered agritourisms are reported in Tables 15.5 and 15.6.

Table 15.5. Proposed interventions costs and environmental benefits for *Villa Dafne* agritourism.

ARERA Datasheet N.	**EU Ecolabel Points**	**Proposed Intervention Cost (€)**	**Energy Savings (*AES*)**	**CO_2 Emissions Reduction (tCO_2eq/Year)**	**Economic Savings (€/Year)**
5	4	123,971.09	6.20%	7.7	2831.21
7	3.5	37,588.70	18.26%	18.6	8053.63
8T	2	13,392.91	11.00%	11.2	4851.56
15T	1.5	98,026.40	7.37%	10.0	3429.31
19T	3.5		1.67%	1.7	738.75
27T	1.5	20,930.15	8.80%	9.0	3881.25
6	-	81,172.42	17.55%	23.9	738.74
20T	-		3.13%	3.2	1381.90

Table 15.6. Proposed interventions costs and environmental benefits for *Bergi* agritourism.

ARERA Datasheet N.	EU Ecolabel Points	Proposed Intervention Cost (€)	Energy Savings (*AES*)	CO_2 Emissions Reduction (tCO_2eq/Year)	Economic Savings (€/Year)
5	4	95,980.90	3.70%	2.73	1350.79
7	3.5	37,588.70	25.35%	18.59	8053.63
8T	2	14,608.10	11.00%	8.18	4595.95
15T	1.5	73,519.80	6.29%	4.69	2767.13
19T	3.5		1.74%	1.28	554.06
27T	1.5	10,182.10	6.00%	4.40	1905.96
6	-	81,854.11	13.16%	9.81	1212.67
20T	-		4.39%	3.22	1393.51

As can be observed, according to what has been previously pointed out, a single intervention cost was given to datasheets 15T and 19T as the proposed intervention corresponds to the same type of system, i.e., the same system allows operation for both heating and cooling. The same consideration can be made for datasheets 6 and 20T in relation to the insulation of the building.

Looking at the economic savings column it can be noticed how, from this point of view greater advantages can be associated with datasheets 7 and 8T, followed by 15T + 19T, 27T and lastly 5. Considering the whole set of interventions, instead, the (6 + 20T) option would also result second in this case.

Referring to CO_2 emissions reduction, the obtained results are obviously in line with what was seen beforehand (Figures 15.2 and 15.3) and commented on with the energy savings.

15.4 Discussion

The application of the ARERA data sheets to agritourism raises a question concerning the suitability of these simplified forms to the energy performances of agritourisms sites, being originally developed for residential and commercial buildings.

On the other hand, a possible improvement of the energy features of an agritourism, due to the actions referred to in the ARERA datasheets, should be evaluated on the base of its effectiveness in addressing a given site, towards a nearly-zero energy path, as required by the current international standards [20,21,28].

Both issues are briefly discussed in the following.

15.4.1 Effectiveness of the Proposed Actions

The obtained results could seem not too encouraging in terms of energy savings. In fact, the reduction of the energy demand following the proposed actions accounts for about one third of the annual energy consumption for both the considered agritourisms. However, this is not surprising; the fact that the ARERA technical datasheets proposed interventions have been designed for the residential sector, in fact, place some limits on their application in a wider context, such as the agritourism one. Specifically, the limitations set on the reference physical units (UFRs) sizes might have made the outcomes much lower than the actually achievable results.

For instance, concerning datasheet 7 a maximum kW_p of 20 kW is reductive for an agritourism, which could employ PV better having wide areas available to install such systems. Supporting this observation, during the survey of the agritourisms, it arose that both currently have a 100-kW PV undergoing design phase. In this context it would be more sensible to impose a limit on the maximum percentage of yearly energy consumption to be covered with the proposed intervention.

The latter consideration also applies to datasheet 8T.

Regarding, instead, datasheet 15T the application problem is mainly related to the residential standard apartment size (80–90 m^2), which is difficult to translate into an agritourism setting. In the conducted analysis, for instance, in order to comply with such a parameter, three to four rooms were grouped and assumed equal to 1.5 standard apartments, but it could be a questionable criterion.

As for datasheets 19T, it would be more reasonable to install a centralized system rather than considering the replacement of the single air conditioning units (the same goes for the heat pumps proposed by datasheets 15T).

Nevertheless, since one of the aims of this work was that of singling the most convenient EU Ecolabel “environmental actions packages”, based on the comparison of the results reported in Tables 15.5 and 15.6 it was decided to tentatively choose three alternative options, both for *Villa Dafne* (*VD-n*) and *Bergi* (*B-n*), as follows:

- options *VD-1* and *B-1*, constituted by datasheets number 5 and 7;
- options *VD-2* and *B-2*, constituted by datasheets number 7, 8T and (15T + 19T), the latter two must be considered together for the reasons indicated at the end of Section 15.2.4.2.;
- options *VD-3* and B-*3*, constituted by datasheets number 7, (15T + 19T) and 27T.

Table 15.7 summarizes the obtained results relative to the selected “environmental actions packages”.

Table 15.7. Summarized results for the two agritourisms.

Agrit.	Environm. Actions Package	EU Ecolabel Points	Environmental Actions Package Cost (€)	Energy Savings (*AES*)	CO_2 Emissions Reduction (tCO_2eq/Year)	Economic Savings (€/Year)	Pay Back Period—Not Discounted (Years)
Villa Dafne	*VD-1*	7.5	161,559.79	24.46%	26.3	10,884.84	14.8
	VD-2	10.5	149,008.01	36.63%	39.8	16,334.51	9.1
	VD-3	10	156,545.25	34.43%	37.6	15,364.20	10.2
Bergi	*B-1*	7.5	133,569.60	29.05%	21.3	9,404.42	14.2
	B-2	10.5	125,716.60	42.64%	31.5	15,416.72	8.2
	B-3	10	121,290.60	37.64%	27.7	12,726.73	9.5

By analyzing the data reported in Table 15.7 it was, therefore decided to consider as optimal options *VD-2* for *Villa Dafne* and *B-2* for *Bergi*. These two options allow, in fact, the obtaining of greater economic and energy savings and, correspondingly, higher CO_2 emissions reductions. Moreover, they are characterized by the lower pay back periods.

It must be observed that the availability of effective and reliable methods for evaluating the energy actions involving agritourism is of paramount importance for suitable planning of this important sector. Therefore, the ARERA technical data sheets should be properly reconsidered in order to render them more complicit with the energy features of agritourism buildings and dwellings.

15.4.2 Towards a Nearly Zero Energy Agritourism

As already mentioned, another intention of this work concerned the possibility of applying some actions to the agritourism structures, additional to those envisioned by the EU Ecolabel, in order to move towards a potential "nearly Zero Energy Agritourism (nZEA)". For this purpose, the results relative to ARERA datasheets 6 and 20T were added to the selected optimal options *VD-2* and *B-2* for *Villa Dafne* and *Bergi*, respectively; the outcomes of such combinations are reported in Figures 15.4 and 15.5.

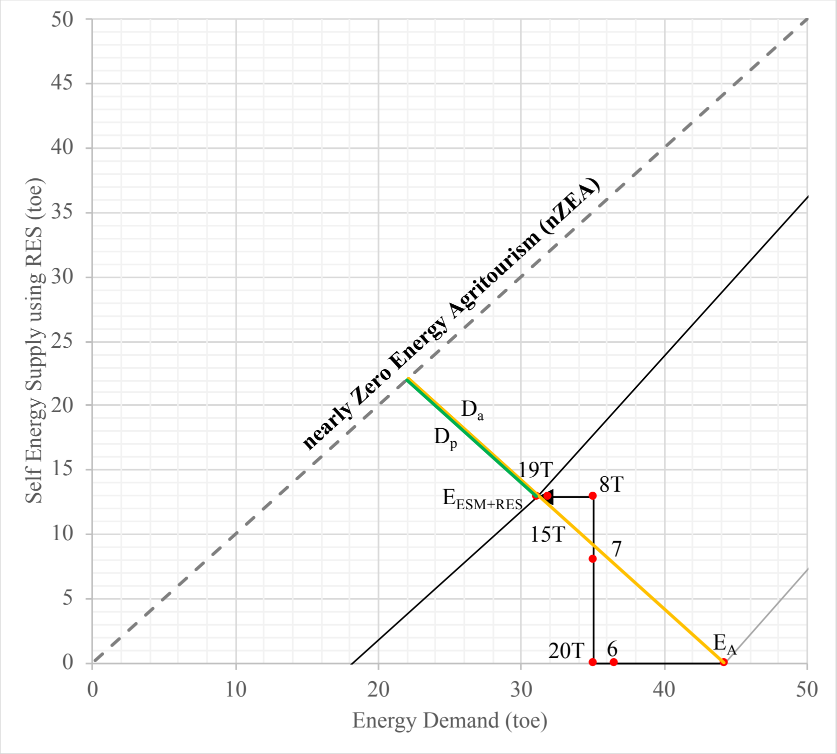

Figure 15.4. Path towards a nearly zero energy condition (nZEA) for *Villa Dafne*.

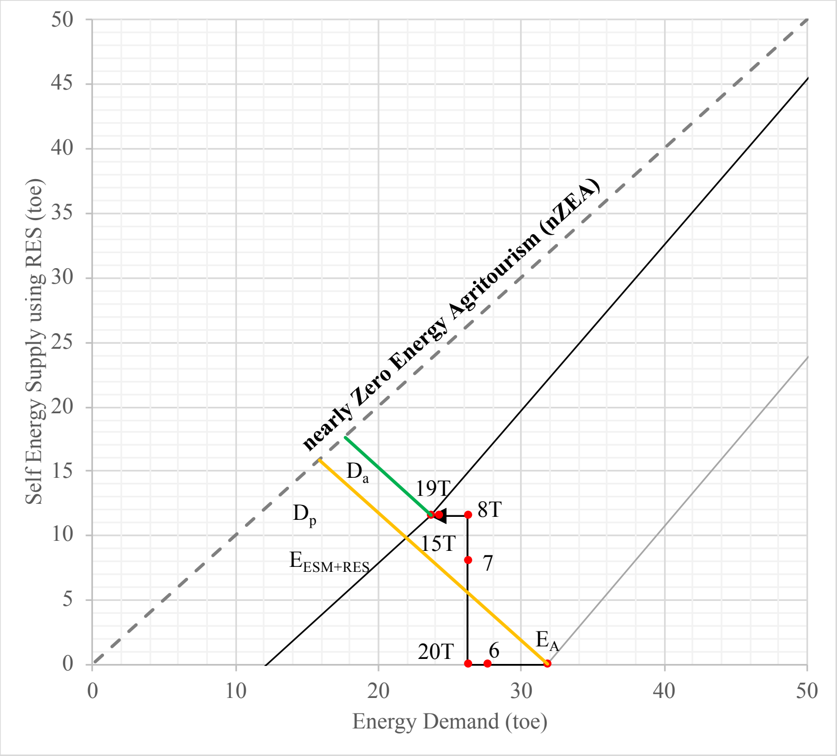

Figure 15.5. Path towards a nearly zero energy condition (nZEA) for *Bergi*.

According to such approaches and visual representations, already used in the literature [68–70], the nearly zero energy condition (nZEA) is reached when the energy demand (reported on the x axis) is completely covered by the self-energy supply from renewable sources (reported on the y axis).

Therefore, the effectiveness of the ARERA proposed interventions in moving agritourism towards a sustainable path, nZEA, is given as a simple summation of the effects provided by the energy saving measures—E_{ESM} (datasheets 6, 15T, 19T, and 20T) and those attributable to the renewable energy sources—E_{RES} (datasheets 7 and 8T). E_A represents, instead, the current energy consumption and, D_a and D_p the current (ante operam) and achievable (post operam) minimum distances (hence the perpendicularity) from the nZEA condition, respectively.

For the sake of simplicity, this assumption does not take into account the synergetic effects that are likely induced by the contemporary adoption of different energy actions on a given agritourism site.

Consequently, the results reported in Figures 15.4 and 15.5 show that the selected combinations of interventions allow an improvement of 59% for *Villa Dafne* and a 62% for *Bergi,* in terms of approaching the nZEA condition with respect to the current conditions.

Regardless of the obtained results, the proposed methodology can be seen as a simplified scheme for analyzing and ranking the “environmental actions packages” applicable to agritourisms, and could be usefully adopted by local administrations to define the impact of different scenarios in order to better define environmental policies concerning the agritourism sector.

The proposed assessment/estimation methodology could, therefore, also represent important information for the design of the rural tourism sector, and of the/a regional energy plan by stakeholders and decision makers [71,72].

15.4.3 On the Correspondence between the EU Ecolabel Criteria and the ARERA Technical Datasheets

The application of the ARERA technical datasheets and the EU Ecolabel criteria to two different agritourisms in Sicily (here considered representative of the whole regional agritourism context) enabled us to better understand the level of compliance between two such schemes. The level of correspondence cannot totally match, since the ARERA methodology has been designed specifically for residential buildings and, on the other hand, the EU Ecolabel for Tourist Accommodation Services applies expressly to tourism facilities, with features that could not be perfectly applicable to agritourisms. These latter, in fact, are generally characterized by the presence of cultivated soils and the production of agrifarm foods and products.

Nevertheless, the comparison exerted on the two sites has shown that some useful correspondences can be assessed. In fact, by means of the combination of the ARERA technical datasheets and the EU Ecolabel energy optional criteria, it is likely possible to identify some “environmental actions packages”, suitable to the agritourism context. Such packages are allowed to obtain a 7.34 points minimum limit for the energy category, set by European regulation. In particular, it emerged that the combination of datasheets 5 and 7 (options *VD-1* and *B-1*) allowed obtaining 7.5 EU Ecolabel points, while by adding datasheets 7, 8T and 15T + 19T (options *VD-2* and *B-2*) it is possible to achieve 10.5 points, and from the union of datasheets 7, 15T + 19T, and 27T (options *VD-3* and *B-3*) a total of 10 points can be reached.

Therefore, a suitable implementation of the ARERA technical datasheets (that, apart from other things, permits an easy computation of the energy performances of various building and system components) is recommended to be ancillary utilized with the EU criteria in order to assess a unique scheme for the application of the EU Ecolabel brand.

In addition, the above verified correspondence, allowed us to introduce a criterion for ranking the effectiveness of the proposed measures within the framework of the nearly Zero Energy Buildings approach (nearly Zero Energy Agritourism, in this case). In other words, once the ARERA datasheets have provided useful energy saving results, achieved thanks to the implementation of the proposed interventions, it is easy to report such results in terms of closeness to a zero energy situation for a given agritourism.

15.5 Conclusions

Agritourisms represent an important reality in the Italian tourism sector, specifically in Sicily due to their numerical consistency and constantly growing trend. The idea at the base of the presented work stems from some considerations regarding the use of a simple method, based on the ARERA technical datasheets (which constitute an official Italian reference), to assess the energy, environmental, and economic benefits related to the implementation of some energy efficiency measures on a given agritourism, specifically aimed at achieving the EU Ecolabel environmental excellence brand, in the perspective of approaching a potential nearly Zero Energy condition.

The results of the conducted analysis put in evidence some discrepancies regarding the application of the ARERA calculation methods, devised for the residential sector, in a wider context, like that of agritourism. Such an outcome was foreseeable, but it has probably been highlighted even more by the fact that the datasheets results are outdated, having not been updated in the last few years.

Nevertheless, the adoption of the proposed efficiency interventions, despite not being specifically defined for the agritourism context, contributed in addressing both structures toward a nearly Zero Energy path, hence, improving their performances in terms of sustainability.

Apart from the interventions proposed by the ARERA, clearly agritourism sites can be interested in further renewable technologies in order to promote their energy sustainability. In fact, the application of solutions like micro wind turbines, biomass, and high efficiency cogeneration for such purposes has been demonstrated [73]. Similar and/or recently available technologies could represent a driver for implementing new ARERA technical datasheets, in order to render them more compliant with the agritourism context, and the EU targets for energy efficiency and emissions reductions in the civil sector.

In conclusion, it arose that, although it was possible to combine the ARERA technical datasheets with the EU Ecolabel criteria, in order to apply the proposed analysis methodology to the agritourism context in a more efficient way, the existing ARERA technical datasheets should be suitably updated and/or replaced by other more effective tools, expressly planned for the accommodation and catering business sector.

Chapter 15 Acknowledgment

This work was carried out within the research funds provided by the XXXIII Cycle Doctoral Course in Energy and Information Technologies of the University of Palermo.

Chapter 15 Aappendices

Appendix 15.A

Table 15.A1. ARERA technical datasheets.

Datasheet N°	Proposed Action
1-tris	Installation of high-quality compact fluorescent lamps, not exceeding 15 W power
2	Replacement of electric water heater with gas water heater with sealed chamber and piezoelectric ignition
3	New installation of 4-star single-family efficiency boiler fueled with natural gas
4	Replacement of gas water heater (with open chamber and pilot flame) with gas water heater (with sealed chamber and piezoelectric ignition)
5	Replacement of simple glazing with double glazing
6	Wall and roof insulation
7	Use of photovoltaic systems with an electrical power of less than 20 kW
8T	Installation of solar collectors for the production of domestic hot water
9T	Installation of electronic frequency regulation systems (inverters) in electric motors operating on pumping systems with power lower than 22 kW
10T	Electricity recovery from natural gas decompression
11T	Installation of engines with higher efficiency

13a-bis	Installation, in residential environments, of water saving kits consisting of low-flow aerators and low-flow shower heads
13b-bis	Installation of low flow shower dispensers in hotels and guest houses
13c-bis	Installation of low flow shower dispensers in sports facilities
15T	Installation of outdoor air electric heat pumps instead of boilers in newly built or renovated residential buildings
16T	Installation of electronic frequency regulation systems (inverters) in electric motors operating on pumping systems with power greater than or equal to 22 kW
17T	Installation of luminous flux regulators for mercury vapor lamps and high-pressure sodium vapor lamps in outdoor lighting systems
18T	Replacement of mercury vapor lamps with high pressure sodium vapor lamps in public lighting systems
19T	Installation of high efficiency outdoor air conditioners with cooling capacity lower than 12 kW_f
20T	Thermal insulation of walls and roofs for summer cooling in domestic and service sectors
21T	Application in the civil sector of small cogeneration systems for winter and summer air-conditioning of rooms and the production of domestic hot water
22T	Application in the civil sector of district heating systems for room air conditioning and domestic hot water production
23T	Replacement of incandescent traffic lights with LED traffic lights
24T	Replacement of incandescent votive lamps with votive LED lamps
25Ta	Installation of devices for automatically switching off equipment in standby mode in the residential sector
25Tb	Installation of devices for automatically switching off equipment in stand-by mode in the hotel sector
26T	Installation of centralized systems for winter and/or summer air conditioning in civil use buildings
27T	Installation of electric heat pump for domestic hot water production in new and existing plants
28T	Realization of high efficiency systems for the illumination of main motorway and extra-urban tunnels
29Ta	Implementation of new high-efficiency lighting systems for roads destined to motorized traffic
29Tb	Installation of high efficiency lighting fixtures in existing lighting systems for roads destined to motorized traffic

Table 15.A2. EU Ecolabel for Tourist Accommodation Services criteria.

	Mandatory		**Optional**
General management criteria			
1	Basis of an Environmental Management System	23	EMAS registration, ISO certification of the tourist accommodation (up to 5 points)
2	Staff training	24	EMAS registration or ISO certification of suppliers (up to 5 points)
3	Information to guests	25	Ecolabelled services (up to 4 points)
4	General maintenance	26	Environmental and social communication and education (up to 2 points)
5	Consumption monitoring	27	Consumption monitoring: Energy and water sub-metering (up to 2 points)
Energy criteria			
6	Energy efficient space heating and water heating appliances	28	Energy efficient space heating and water heating appliances (up to 3 points)
7	Energy efficient air conditioning and air-based heat pumps appliances	29	Energy efficient air conditioning and air-based heat pumps appliances (up to 3.5 points)
8	Energy efficient lighting	30	Air-based heat pumps up to 100 kW heat output (3 points)
9	Thermoregulation	31	Energy efficient household appliances and lighting (up to 4 points)
10	Automatic switching off of HVAC and lighting	32	Heat recovery (up to 3 points)
11	Outside heating and air conditioning appliances	33	Thermoregulation and window insulation (up to 4 points)
12	Procurement of electricity from a renewable electricity supplier	34	Automatic switch off appliances/devices (up to 4.5 points)
13	Coal and heating oils	35	District heating/cooling and cooling from cogeneration (up to 4 points)

		36	Electric hand driers with proximity sensor (1 point)
		37	Space Heater emissions (1.5 points)
		38	Procurement of electricity from a renewable electricity supplier (up to 4 points)
		39	On site self-generation of electricity through renewable energy sources (up to 5 points)
		40	Heating energy from renewable energy sources (up to 3.5 points)
		41	Swimming pool heating (up to 1.5 points)
Water criteria			
14	Efficient water fittings: Bathroom taps and showers	42	Efficient water fittings: Bathroom taps and showers (up to 4 points)
15	Efficient water fittings: Toilets and urinals	43	Efficient water fittings: Toilets and urinals (up to 4.5 points)
16	Reduction in laundry achieved through reuse of towels and bedclothes	44	Dishwasher water consumption (2.5 points)
		45	Washing machine water consumption (3 points)
		46	Indications on water hardness (up to 1.5 points)
		47	Optimised pool management (up to 2.5 points)
		48	Rainwater and grey water recycling (up to 3 points)
		49	Efficient irrigation (1.5 points)
		50	Native or non-invasive alien species used in outdoor planting (up to 2 points)
Waste and wastewater criteria			
17	Waste prevention: Food service waste reduction plan	51	Paper Products (up to 2 points)
18	Waste prevention: Disposable items	52	Durable goods (up to 4 points)
19	Waste sorting and sending for recycling	53	Beverages provision (2 points)
		54	Detergents and toiletries procurement (up to 2 points)
		55	Minimisation of the use of cleaning products (1.5 point)
		56	De-icing (1 point)
		57	Used textiles and furniture (up to 2 points)
		58	Composting (up to 2 points)
		59	Waste water treatment (up to 3 points)
Other criteria			
20	No smoking in common areas	60	No smoking in rooms (1 point)
21	Promotion of environmentally preferable means of transport	61	Social policy (up to 2 points)
22	Information appearing on the EU Ecolabel	62	Maintenance vehicles (1 point)
		63	Environmentally preferable means of transport offer (up to 2.5 points)
		64	Unsealed surfaces (1 point)
		65	Local and organic products (up to 4 points)
		66	Pesticide avoidance (2 points)
		67	Additional environmental and social actions (up to 3 points)

Appendix 15.B

In the following the equations relating to the ARERA calculation procedures for each considered technical datasheet are given, in order to define the parameters reported in the following, Table 15.B1.

Datasheet N° 5, “Replacement of simple glazing with double glazing”, allows obtaining the gross primary energy savings (*RL*) achievable per individual building:

$$RL = RSL \times S_{window}\ [toe/year/building] \tag{15.B1}$$

where:

- RSL is the specific gross primary energy savings per m^2 of replaced glass surface, dependent on the climatic zone and the buildings intended use (residential, office, school, hospital, etc.), expressed in toe/year/m^2;
- S_{window} is the replaced glass surface, expressed in m^2.

Datasheet N° 7, “Use of photovoltaic systems with an electrical power of less than 20 kW”, allows obtaining the achievable specific gross primary energy savings (*RSL*) for each reference physical unit (*UFR*), represented by a photovoltaic system with electrical power <20 kW:

$$RSL = kW_p \times h_{eq} \times k_1 \times 0.22 \cdot 10^{-3}\ [toe/year] \tag{15.B2}$$

where:

- kW_p is the peak power of the system, expressed in kW;
- h_{eq} is a coefficient dependent on the solar belt of the considered province, expressed in h/year;
- k_1 is a dimensionless coefficient that varies in function of the inclination (β) of the photovoltaic modules on to the horizontal plane, that is $k_1 = 0.70$ for $\beta > 70°$, otherwise $k_1 = 1$;

Datasheet N° 8T, “Installation of solar collectors for the production of domestic hot water”, allows obtaining the annual shares of primary net energy savings (RN_C) for each reference physical unit (*UFR*), represented by the opening surface (m^2) of the installed collectors:

$$RL = RSL \times S_{window}\ [toe/year/building] \tag{15.B3}$$

where:

- RSN is the net specific primary energy savings achievable per m^2 of UFR, based on the system typology and on the solar belt to which the site belongs, expressed in toe/year/m^2;

<u>Datasheet N° 15T</u>, “Installation of outdoor air electric heat pumps instead of boilers in newly built or renovated residential buildings”, allows obtaining the annual shares of primary net energy savings (RN_C) for each reference physical unit (UFR), represented by a standard apartment, which in terms of square meters of heated surface corresponds to about 80–90 m^2:

$$RN_C = a \times RSL \times UFR\ [toe/year] \tag{15.B4}$$

where:

- a is the additionality coefficient (dimensionless);
- RSL is the specific gross primary energy savings per single UFR, based on the COP of the heat pump typology, the surface/volume (S/V) ratio of the heated environment and the climatic zone (c.z.), expressed in toe/year/m^2.

<u>Datasheet N° 19T</u>, “Installation of high efficiency outdoor air conditioners with cooling capacity lower than 12 kW$_f$”, allows obtaining the annual shares of primary net energy savings (RN_C) for each reference physical unit (UFR), represented by 1 kW cooling capacity of the air conditioning system at nominal conditions (expressed in actual installed cooling capacity):

$$RN_C = a \times RSL \times UFR\ [toe/year] \tag{15.B5}$$

where:

- a is the additionality coefficient (dimensionless);
- RSL is the specific gross primary energy savings per UFR, dependent on the solar belt of the considered province, expressed in toe/year/m^2.

<u>Datasheet N° 27T</u>, “Installation of electric heat pump for domestic hot water production in new and existing plants”, allows obtaining the annual shares of primary net energy savings (RN_C) for each reference physical unit (UFR), represented by an electric heat pump water heater for the production of domestic hot water (expressed in number of units):

$$RN_C = a \times RSL \times UFR\ [toe/year] \tag{15.B6}$$

where:

- a is the additionality coefficient (dimensionless);
- RSL is the specific gross primary energy savings per single UFR, based on the COP of the heat pump typology and on the climatic zone, expressed in toe/year/m^2.

Datasheet N° 6, "Wall and roof insulation", allows obtaining the gross primary energy savings (RL) achievable per insulated surface unit (m^2):

$$RL = RSL \times S_{wall-roof}\ [toe/year/building] \tag{15.B7}$$

where:

- RSL is the specific gross primary energy savings per m^2 of insulated surface, dependent on the climatic zone and the building intended use (residential, office, school, hospital, etc.), expressed in toe/year/m^2;
- $S_{wall\text{-}roof}$ is the insulated surface of walls and/or roof, expressed in m^2.

Datasheet N° 20T, "Thermal insulation of walls and roofs for summer cooling in domestic and service sectors", allows obtaining the annual shares of primary net energy savings (RN_C) achievable per m^2 of insulated surface unit (UFR):

$$RN_C = a \times RSL \times UFR\ [toe/year] \tag{15.B8}$$

where:

- a is the additionality coefficient (dimensionless);
- RSL is the specific gross primary energy savings per m^2 of insulated surface, based on the thermal transmittance K (W/m^2/K) of the structure (walls and/or) before the intervention, expressed in toe/year/m^2.

- **Table 15.B1.** EU Ecolabel for Tourist Accommodation Services criteria calculations.

Data-Sheet N. (Eq)	*Villa Dafne*		*Bergi*	
	Equation Input Data	**Equation Result**	**Equation Input Data**	**Equation Result**
5 (15.B1)	RSL = 0.009 toe/year/m^2 S_{window} = 305 m^2	RL = 2.7 toe/year	RSL = 0.005 toe/year/m^2 S_{window} = 236 m^2	RL = 1.2 toe/year
7 (15.B2)	kWp = 19.9 kW h_{eq} = 1852 h/year k_1 = 1	RSL = 8.1 toe/year	kWp = 19.9 kW h_{eq} = 1852 h/year k_1 = 1	RSL = 8.1 toe/year
8T (15.B3)	$RSN_{electrical}$ = 0.210 toe/year/m^2 RSN_{gas} = 0.123 toe/year/m^2 $UFR_{electrical}$ = 23 m^2 UFR_{gas} = 0	RN_C = 4.9 toe/year	$RSN_{electrical}$ = 0.210 toe/year/m^2 RSN_{gas} = 0.123 toe/year/m^2 $UFR_{electrical}$ = 5 m^2 UFR_{gas} = 21 m^2	RN_C = 3.5 toe/year

15T (15.B4)	$a = 1$ RSL = 0.181 toe/year/UFR UFR = 18	RN_C = 3.3 toe/year	$a = 1$ RSL = 0.143 toe/year/UFR UFR = 14	RN_C = 2.0 toe/year
19T (15.B5)	$a = 1$ RSL = 0.0037 toe/year/UFR UFR = 200 kWf	RN_C = 0.7 toe/year	$a = 1$ RSL = 0.0037 toe/year/UFR UFR = 150 kWf	RN_C = 0.6 toe/year
27T (15.B6)	$a = 1$ RSL = 0.106 toe/year/UFR UFR = 37	RN_C = 3.9 toe/year	$a = 1$ RSL = 0.107 toe/year/UFR UFR = 18	RN_C = 1.9 toe/year
6 (15.B7)	RSL = 0.0028 toe/year/m^2 $S_{wall\text{-}roof}$ = 2768.5 m^2	RL = 7.8 toe/year	RSL = 0.0015 toe/year/m^2 $S_{wall\text{-}roof}$ = 2791.75 m^2	RL = 4.2 toe/year
20T (15.B8)	$a = 1$ RSL = 0.0005 toe/year/UFR UFR = 2768.5 m^2	RN_C = 1.4 toe/year	$a = 1$ RSL = 0.0005 toe/year/UFR UFR = 2791.75 m^2	RN_C = 1.4 toe/year

Chapter 15 References

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SECTION III.B – Results and Findings

This section introduced an approach to assess the effectiveness of the application of the European Ecolabel brand, by employing the simplified ARERA (Italian Regulatory Authority for Energy Networks and Environment) calculation methodologies, in order to move agritourisms towards a nearly zero energy and environmentally sustainable path. From the obtained findings the following remarks can be done:

- the proposed approach resulted effective in moving agritourism towards a sustainable path (“nearly Zero Energy Agritourism – nZEA)”. Specifically, results showed an improvement of 59% and a 62% for the two examined agritourisms, in terms of approaching the nZEA condition with respect to the current conditions;
- the fact that the ARERA technical spreadatasheets have been designed for the residential sector placed some limits on their application in the wider agritourism context. In particular, the limitations set on the reference physical units (UFRs) sizes might have made the outcomes much lower than the actually achievable results.

PART III – Conclusion

This third part of the dissertation focused on two types of buildings that represent an important reality in the Italian construction panorama, for both economic and historical reasons, namely tourism (precisely agritourism) and historical buildings, specifically those hosting museums and/or exhibition halls.

The outcomes of the studies presented in this section, confirmed how, given the numerosity of such building typologies on the territory, hence the fact that they represent a significant share of the energy consumers in the tertiary sector, proper attention should be given to the measures, and assessment methodologies, purposely intended for them.

The main results and findings, which were briefly summarized at the end of each section, will be further discussed and contextualized in the general framework of the dissertation in the conclusive Part IV.

PART IV –Lessons Learned and Future Developments

This conclusive fourth part of the dissertation highlights the main findings and possible future developments of the work carried out during the PhD course. It is composed of two sections. Section IV.A, which summarizes the lessons learned from the presented fifteen chapters and some possible future research developments, is divided according to the structure in which the dissertation has been organized. While Section IV.B contains the final general observations and conclusions.

IV.A – Lessons Learned

Part I – Interventions on Single Buildings

A strategy to improve the energy efficiency, environmental performance and resilience of single buildings consists in providing them with solutions aimed at accomplishing a better mitigation and adaptation to the actual climate change and also consuming less energy. Within such scenario, buildings external components are those more subjected to the atmospheric agents suddenly variations and, at the same time, they constitute the elements on which it is most immediate to intervene, especially in the case of existing buildings. Of course, such solutions aimed at improve the energy efficiency and environmental performance of buildings must also guarantee indoor thermal comfort conditions to occupants. On this purpose, in this first part of the dissertation some interventions were presented.

Among the investigated measures, envelope components employing new types of environment-friendly composites, containing vegetal matters and ecological waste resulting from recycling activities, showed to have good insulation properties, making these new assemblies a quite promising and practicable alternative to the mostly used traditional insulating materials. However, in order to have a more comprehensive evaluation, other analyses should be carried out aimed at evaluating the mechanical resistance, the impact of moisture content and the influence of the drying process on the thermal and mechanical properties. In addition, further analyses are also recommended to optimize the preparation process in order to make them even more sustainable in terms of minimal use of extracted raw material, energy efficiency and net-zero emissions. In this direction further developments of the research activity have been planned.

Green roofs represent another solution that was in-depth analysed in this part of the dissertation, under different points of view.

The use of an environment-friendly material has also been treated in this case, that is coconut fibers – CF as insulators as an alternative to the common synthetic materials (such as expanded polystyrene – EPS). In terms of thermal performance CF behavior resulted being comparable to those of other natural and synthetic materials commonly used. The doubts on their applications are mostly related to the technological solutions to adopt for their implementation in the manufacturing market and their diffusion as building materials. As a case in point, the fact that there is no certified information about CF thermohygrometric behavior can be a deterrent in their employment and, therefore, needs further and separate and specific evaluation. As does the CF behavior in the presence (or absence) of diverse grass and vegetal plant species on the roof, by mean of experimental measuring campaign (including in situ measurements) to determine their energy conduct.

The green roofs effectiveness as tools for improving the indoor comfort levels was also examined. The on-field experiments showed that green roofs actually contribute to the mitigation of the indoor air temperatures, thus producing an improvement of the comfort conditions, especially during summer seasons; while some criticalities during transition periods emerged. Furthermore, the availability of field data put into evidence the importance of selecting a proper plant species during the green roof design phase. On the other hand, some limits were also noticed mainly represented by the lack of adequate simulation tools able to facilitate the green roof design and assessment processes.

To give an overall evaluation on green roofs environmental performance, the life cycle assessment – LCA methodology was also utilized. The results of the assessment confirmed that, in the considered contexts. the highest environmental impacts are attributable to the production phase. However, it must be noted that the end-of-life phase of the green roof (which has not been accounted for here due to the lack of precise information) is currently being investigated in detail as further advancement in the analysis, by also considering the disposal of the green roof components and the related cost of transportation to the disposal site. The application of the LCA allowed to also point out some other aspects on which more attention should be paid, as for instance the evaluation of the initial high construction and maintenance costs in sight of a proper economical evaluation.

Given that nowdays people tend to spend more and more time indoor, when considering solutions aimed at improving the energy efficiency and environmental performance of buildings, not only the thermal comfort conditions must be guaranteed, but also those regarding other important aspects for the occupants.

On this subject, the lighting aspect was analysed, specifically the relationship between LED (Light Emitting Diode) lamp characteristics and *non image-forming* human reactions. In fact, LED lamps represent the best available technology in terms of lighting and energy efficiency, but much remains to be investigated on those other elements not strictly related to the visual aspects but still having a strong influence on the visual comfort and that can be summarized in a parameter defined as circadian stimulus – *CS*. The experiments obtained final results allowed to find some usefull correlations among *CS* and LED characteristics, confirming that such relationship is a complicated one, which need to be further developed and deepened in the future, possibly also integrating the medical/neurological aspects (with the support of experts in the field) in order to obtain a more complete assessment.

As well as making a more efficient use of traditional sources by improving energy savings, renewable energy sources – RES represent an important instrument for rendering buildings more sustainable and resilient.

That is why one chapter dealt with photovoltaic-thermal systems (PV/T). In particular the effect of the thermal storage dimensions on the energy performance of the system was deepened by means of a parametric analysis, taking into account the possible ranges of values which may be assumed by the variables/parameters used to describe the operation of the system, in correspondence of various conditions. The results of the analysis proven PV/T as a RES technology having a great potential as cogeneration devices able to generate electrical and thermal outputs at the same time. The conclusive remarks may provide useful information and can be exploited by designers and researchers to maximize the efficiency of the systems. Additional research is also needed to draw definitive conclusions on this topic, especially when economic considerations are involved or the effects of the climatic conditions are considered, also in comparison with experimental data. In this direction, a development of this research is actually being planned.

As previously mentioned, another aspect worthy of attention is the climatic context in which a building is sited, having a strong influence on the structure environmental performance.

With a view on this, (i) some considerations about an indicator aimed at describing the energy efficiency of buildings with innovative envelope components at different climatic conditions, and (ii) a comparison of the indoor performances of a building equipped with different roof configurations in diverse Italian sites, were also included in this part of the dissertation. Findings from point (i) indicate that, contrary to traditional and cool roofs, for buildings equipped with green roofs, characterized by dynamic features, it would likely be more appropriate to use an indicator that considers the time variability of vegetation-related parameters. As for point (ii), the use of the "Climatic Severity Index" (recently introduced by an Italian technical standard) did not prove to always be easily applicable, since it led to the unusual observation that some actions implemented for improving the energy efficiency have on occasion resulted in a worsening of the indoor comfort. Thus, the outcomes of the carried-out work represent a starting point and might provide a contribution for the development process of a new indicator, particularly concerning how to account for the relationship between the indoor microclimate conditions and their effects on the energy performances of buildings.

A fundamental step when implementing measures and strategies for improving the environmental performance of buildings, is represented by the evaluation of their energy behavior; it is, then, important to have sound tools to do such an esteem.

To this purpose, last but not least, this part of the dissertation concluded by reporting an assessment of the evolution of the European Standards for the calculation of energy efficiency in buildings.

The conducted analysis evidentiated how, although the recently publicated EN ISO 52016 allow to performe a more detailed evaluation with respect to the still in use EN ISO 13790, some aspects of the EN ISO 52016 should be investigated more thoroughly. Specifically, the new approach used to calculate the thermal storage capacities of the single elements and the distribution of the solar gains between the radiative component and the convective component. As a future development, on the single building scale standpoint, the simulation model could be extended to multiple thermal zones, taking into account different usage and boundary conditions for separate parts of the investigated structure.

Broadening the perspective instead, from a cluster of buildings point of view (theme of Part II of the dissertation), a further step could consist in the improvement of the model in order to consider how different buldings close to each other influence their respective energy efficiencies, also in terms of final energy utilization.

Part II – Interventions on Cluster of Buildings

The research work shown in this part of the dissertation started from the intent to widen the the concepts of energy efficiency, environmental performance of buildings going from the single structure to a clustered group of them, in view of achieving a more comprehensive urban resilience.

In the first of the two reported case studies, about the promotion and adoption of some energy efficiency strategies at the University of Palermo campus, a Campus Demotechnic Index (CDI) has been introduced as a usefull tool in order to provide a comprehensive evaluation of the energy performance of the campus. Thanks to such index it was possible to evaluate how by means of the actions put in place an improvement of the energy savings of about 3%, referring to the original values, has been obtained so far. It is also worth noting that, the future hypothesized equipment and interventions, to be financed with the energy savings coming from the already implemented measures, would allow to achieve approximately 40 tons of avoided CO_2 emissions. Results of this analysis might bring a valuable contribution to the future energy planning of cities. In fact, since campuses reproduce at a little scale the functioning of wider urban contexts, the proposed approach could be effectively adopted by municipality institutions, for example by implementing energy saving measures in the frame of the well-known Energy Service Company – ESCO schemes.

The second case study regarded two other interesting aspects concerning cluster of buildings at the urban scale, that is how vegetated roofs, representing one of the most utilized solutions in terms of sustainability, affect the buildings behaviour in reference to diverse climatic contexts (a big district of Palermo in southern Italy and the small city-centre of Esch-sur-Alzette in Luxembourg), future climate scenarios (2020 – 2050 – 2080 trend) and different socioeconomic and demographic scenarios. The outcomes of the performed investigation confirmed that, with respect to standard roofs, the presence of vegetated roofs allows to obtain energy savings (for both heating and cooling), bring the buildings towards better indoor comfort conditions and decrease of the CO_2 emissions. In particular, it was possible to observe how the extent of such energy-environmental benefits is strongly dependent on the the typology of buildings and on the influence that the geographical and demographic characteristics exert on the considered urban context.

The approaches utilized in this part of the dissertation represent a first step, to be further explored, in the development of procedures for the evaluation of strategies to be implemented in the aim of enhancing resilience at urban scale.

Part III – Tertiary Buildings: Historical and Tourism

As previously remarked, in this third part of the dissertation a specific attention was given to two distinct types of dwellings that represent an important reality in the Italian construction panorama, for both economic and historical reasons, namely tourism (precisely agritourism) and historical buildings, specifically those hosting museums and/or exhibition halls. Given their numerosity on the territory, such kind of buildings represent indeed a significant share of the energy consumers in the tertiary sector.

Regarding museums historical buildings, the implementation of the mathematical model to obtain new indoor quality indicators, to take into account the microclimatic characteristics, the HVAC functioning and, possibly, also the economic aspects, resulted rather promising. Although a critical point might be represented by the difficulty in monetarily quantifying the damage risk related to the artefacts. In order to consider the aspects related to climate characterizing the site where the building is located, a possible future development is represented by the implementation, in a dynamic simulation model, of a function linking the outdoor monitored data with the indoor microclimate conditions, and with information regarding the thermal inertia of the building.

For what concerns the considered agritourism buildings, also in this case quite positive outcomes were obtained from the application of the proposed methodological approach for the calculation of the achievable energy savings, although some discrepancies emerged. The ARERA technical data sheets should, in fact, be properly reconsidered in order to render them more complicit with the energy features of agritourism structures.

Within a more general, regarding the entire building sector, a suitable upgrade of the ARERA technical datasheets is recommended to be ancillary utilized with the EU Ecolabel brand criteria. Furthermore, the proposed methodology can be seen as a simplified scheme for analyzing and ranking the “environmental actions packages” applicable to buildings, and could be usefully adopted by local administrations to define the impact of different scenarios in order to better define building environmental policies compliant with European directives.

IV.B – General Conclusions

The presented work has shown that there is a high potential to improve the energy efficiency, environmental performance and resilience of buildings (and consequently of cities) by promoting the employment of components, systems, technologies and strategies dedicated to supporting and fostering a sustainable optimization of the building sector.

In Chapters 1 to 15 of the dissertation the outcomes of some scientific studies performed during the PhD course, concerning single buildings, cluster of buildings and tertiary buildings, have been reported including their specific discussions, conclusions and recommendations. Moreover, at the end of each Section and Part the most relevant results and findings, lessons learned, limitations and future development (that are planned to be implemented) have been illustrated according to the different areas of interest in which the dissertation has been divided into.

Hence, not to be redundant, this final section summarizes a few overall concluding remarks and outlines some general expected future research lines that could be followed to complement and expand the work carried out so far.

Starting from green roofs, although the work carried out has shown how these constitute an effective and well-established technology in the field of sustainable practices, some aspects to be improved in the future have emerged concerning especially: the need of the availability of specific simulation tools and complete and exhaustive plant species characteristics databases; the possibility of using new eco-compatible materials; the importance of including all the green roof elements life cycle phases in their environmental assessment.

As for the envelope components, identifying and utilize new types of environment-friendly materials with a behavior comparable with those of the more impactful used traditional ones would allow to make a more efficient use of traditional sources by improving energy savings.

On the other hand, the increase in the use of energy from renewable sources (RES) represent an important instrument for improving the environmental performance of the building sector.

It is worth noting that, from the carried out work, it emerged that when applying energy saving technologies it is also important to take into account the climatic context in which these solutions are used and their influence on the indoor comfort conditions, not only from a thermohygrometric point of view but also as regards other characteristics that affect occupants' well-being, as the studies on lighting have shown.

The studies on historic and tourism buildings have also highlighted the importance of considering the peculiarities of the areas in which one operates, in terms of buildings types and of their numerical consistency.

Concerning the cluster of buildings, this subject represented an important part of the performed research work and the one that presents the greatest future prospects regarding the evaluation and implementation of solutions and strategies to increase urban resilience to the challenges bringed by climate change and the other stresses to which such context is subjected. On this topic, the dissertation shows how some interesting results have been obtained, especially about the differences between the different climatic contexts and the possibility of taking into account possible future scenarios, which it would certainly be worthing to investigate and develop further.

Another treated notable theme which needs additional attention is the one regarding the analysis of the European Standards for energy efficiency in buildings, since these can be used as a decision-making support tool by both public administrations and technical experts in the field.

In conclusion, accurate planning (integration of life cycle considerations), construction (use of innovative suitable sustainable materials) and management (improvement of the energy efficiency and dynamic building simulation) of buildings, according to the peculiarities of the sites in which they are located (influence on the achievable energy savings), can contribute to reduce the environmental burden of the building sector and at the same time helping the enhancement of urban resilience. Proper solution sets can, in fact, enable the building resilience against the outdoor stresses and simultaneously guarantee a regenerative indoor environment.

Particularly concerning the ambit of the urban/regional legislation planning, it would be useful to explore (i) the potential for further implementation of sustainable solutions in both new and existing buildings, and (ii) the scale jumping potentials of such strategies, going from the material/component to the building, until the neighbourhood/district all the way up to the entire urban extent.

It would also be sensible to expand the research with the integration of economic and social analyses relative to different sustainable construction materials and energy efficiency strategies, to determine a more comprehensive environmental feasibility in order of establishing a decision principle when promoting one specific solution over another.

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