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Eco-design of emerging BIPV modules based on LCA and LCC

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ABSTRACT

The decarbonization of energy sector requires the substantial contribution of solar photovoltaics (PV), with increasing energy efficiency, feasible production cost while minimizing the environmental impacts. This paper suggests eco-design measures for the innovative building integrated photovoltaics (BIPV) modules by applying life cycle thinking approach. The environmental impacts and costs of BIPV modules based on silicon and perovskite solar cells are quantified and evaluated according to the ISO14040 and ISO14044 standards, the guidelines of International Energy Agency for life cycle assessment (LCA) on solar PV and the Product Environmental Footprint of the European Commission. All the environmental impacts of the BIPV modules are quantified from cradle to grave per 1 kWh of electricity. The same functional unit is applied for life cycle costs, with consideration of manufacturing costs only. Climate change impact of BIPV modules ranges from 2.31E-02 $kgCO_2e$ to 6.83E-01 $kgCO_2e$ per kWh of electricity, depending on their transmittance, materials of the solar cells and end-of-life management strategies. Fossil resource use varies between 2.74E-01 MJ and 1.05E+01 MJ, and mineral and metal resource use is from 1.63E-06 kg Sb eq to 1.14E-04 kg Sb eq per kWh. Besides, levelized cost of electricity generated from BIPV modules ranges from 0.01 EUR to 3 EUR per kWh. The environmental impact and cost assessments of BIPV modules indicate that the eco-design need to improve the efficiency and lifetime of perovskite materials and reduce the cost for cell fabrication, so that they can compete with silicon based BIPV modules.

1. Introduction

The energy sector is among the main sources of greenhouse gas (GHG) emissions. It contributes to about three quarters of GHG emissions in the European Union [1], in which 34 % of the GHG emissions of energy use originates from building sector [2]. To aim at the decarbonization of energy sector and the net zero, the deployment of solar energy technologies, including solar photovoltaics (PV) and concentrating solar power (CSP) should be swiftly increased. According to the net zero scenarios of the International Energy Agency (IEA), by 2050 the electricity generation from solar PV is expected to reach 23 thousand TWh and CSP will contribute 1.3 thousand TWh [3]. These measures not only reduce the GHG emissions but also bring other benefits on energy gains and environmental impacts. For an example, bio-based phase change materials (PCMs) such as slurries of nano-enhanced coconut oil and silver (or gold, aluminium and copper) used in thermal energy storage of solar systems bring higher useful heat gains, compared to pure water [4].

In the building sector, several decarbonization measures related to energy use have been proposed, such as energy efficiency in buildings (i.e. using less energy for building operation for the same performance). For an example, Naghipour and Naghipour optimized the energy consumption in buildings by proper selection of building aspect ratio and orientation, consequently reducing carbon emissions [5]). Other measures include renewable energy generation (e.g. building integrated PV (BIPV), solar thermal collectors), energy storage and flexibility (e.g. smart control, thermal storage system, vehicle batteries, etc.) and energy sufficiency (i.e. optimized use of building) [6]. Among these measures, there is a significant potential for solar energy technologies to contribute to the decarbonization of building sectors, by installing BIPV modules [7]. They are commonly applied for generating renewable energy in renewable energy communities and positive energy district, for examples in four positive energy districts in Norway [6], in the solar neighbourhood in Sweden [8], and in individual buildings [9].

At the same time, solar energy technologies may cause other environmental impacts and depend on some metals and minerals, especially critical and strategic raw materials [10,11]. This is also a concern for emerging solar technologies and BIPV modules based on innovative

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materials. Fortunately, more than 70 % of the environmental impacts such as the carbon footprint, raw material consumption as well as other environmental impacts of these emerging technologies can be estimated since the designing process [12]. These impacts can be minimized through applying the eco-design approach, as a preventative method at the early stage during the design of the technologies in the laboratory.

Due to the importance of BIPV in contributing to the decarbonization of energy and building sectors, and the potential impacts of emerging BIPV modules on the environment, the study quantifies and assesses life cycle environmental impacts and costs of BIPV. The study verifies BIPV advantages of GHG emission reductions, while identifies the weakness (if any) of the technologies in other life cycle environmental impacts, for example toxicity, material consumption and others. Besides, the economic aspects of the emerging BIPV modules are evaluated to support the sustainable development of the technologies. The life cycle approach is selected as it covers all impacts of the technologies' life cycle from raw material extraction, manufacturing, transportation, consumption and their end of life. At the same time, it is a common method for evaluating sustainability in the built environment at both the building and district scale and relevant decarbonization measures applied in the building sector [13,14]. For life cycle environmental impacts, the conventional life cycle assessment (LCA) method will be applied, while life cycle costing (LCC) will be used for the economic evaluation of BIPV. Based on the obtained LCA and LCC results, the paper will suggest eco-design measures for BIPV modules, with focus on the emerging BIPV modules based on silicon and perovskite solar cells.

The technical features and environmental impacts of BIPV modules have been intensively studied in the literature for the last decades. By now, there are two reviews on the technical assessment and economic evaluation of photovoltaics and thermal systems, which cover the BIPV modules [15,16]. Brahim and Jemmi described the photovoltaic thermal (PV/T) systems and considered their payback time, for examples energy payback time, GHG payback time and some other economic indicators such as savings in fossil fuel energy usage, cost of investment and maintenance [16]. Abdelrazik et al. provided the information on the recent advancement of PV/T system applied in buildings (BIPV/T) [15]. The authors gave some insights in the integration of the BIPV/T systems with other systems, such as heating, ventilation and air conditioning, and heat recovery systems, which bring the largest benefit in techno-economic performance, followed by the hybrid of BIPV/T and PCM, and BIPV/T with concentrators. Unfortunately, these reviews do not cover the life cycle environmental impacts of BIPV.

There are several case studies on the environmental impacts of BIPV. Many of those consider the technical, environmental, and economic aspects without applying the life cycle approach. These case studies examined the installation configurations, sites, technologies of applying solar PV on the walls of the buildings and rooftop of parking areas [17], the configuration of building and rooftop PV system [18], different materials for rooftop solar PV [19], combinations of BIPV/T and other systems such as proton exchange membrane [20], heat storage and PCM [21], control process for battery BIPV [22], and combined system of energy storage and rooftop PV [23]. The energy and environmental benefits of these system were verified, with 21 % reduction in annual energy demand for cooling and heat [18], 3.45 % reduction in total energy consumption [23], and carbon emission reduction [17,20–22].

By now, there are 15 case studies applying LCA or LCC on BIPV system. These current studies share three common patterns:

In term of technologies, most of the studied BIPV modules are based on silicon material, with two studies covering conventional thin-film, non-silicon materials such as CIGS and CdTe [24,25]. The most recent study covers the BIPV modules based on new materials such as perovskite [26], but the effort on this new material is limited. There were several efforts for integrating new designs of BIPV modules into the LCA studies, which covers the structure of the systems such as dynamic or adaptive façade [27], combined solar cells with other heat relevant materials or technologies such as heat recovery unit [28], aluminium absorber [29], PCM [30] and textile envelope integrated with flexible PV [31].

In term of LCA methodological choice, most of the studied chose the functional units such as the system, m^2 and year. Only two studies calculated the environmental impacts per kWh of electricity. Besides, the most common indicators are either related to energy or GHG such as cumulative energy demand, energy payback time, energy savings, global warming potential (GWP), GHG emission reductions and GHG payback time. Other environmental impacts such as metal depletion, toxicity attracted less attention and were assessed in six studies [26,27,30,32–34]. The economic aspects of BIPV systems were studied in Refs. [26,31,32].

In term of purpose of the studies, these LCA studies aimed at eco-assessment of the technologies. Though some of these studies include a comparison among the several variants of BIPV modules, none of them proposed measures for eco-improvement of the technologies. As such, the paper contribution can be summarized as.

- Firstly, the LCA and LCC are conducted on BIPV modules based on conventional materials and new materials, e.g. silicon and perovskite.
- Secondly, the study goes beyond the common indicators of energy demand and GHG emissions to cover all life cycle impacts.
- Lastly, by comparing the life cycle environmental impacts, and cost of conventional and innovative BIPV, identify the hotspots during the life cycle of BIPV modules, the study does not limit in eco-assessment, which is the common purpose of LCA application, but also provides useful information for the eco-improvement of the technology.

The key aspects of available LCA studies on BIPV modules are summarized in Table 1.

The paper will support the eco-design of innovative BIPV modules, based on case study of life cycle environmental impacts and cost of BIPV. The studied BIPV modules are silicon solar cells (SSC) and perovskite solar cells (PSC), which are currently studied and demonstrated in Italy under the NEST Spoke 1 project (Network for Sustainable Energy Transition) on Solar PV and CSP/CST. Besides, the paper compared different transmittance, with corresponding power conversion efficiency (PCE) of the cells and roof/façade installations, and end-of-life management strategies such as disposal and recycle. Consequently, this LCA and LCC study will support the further development of the BIPV panel with considerations to their energy benefits, environmental profiles and feasible costs.

In the next section, the data and method will be described, followed by the result section which presents the life cycle environmental impacts with comparison among transmittance, materials of cells and end-of-life treatment of panels, life cycle costs and levelized cost of electricity (LCOE) generated by the BIPV panels, and eco-design measures for emerging BIPV modules. The paper ends with a summary of the main results and insights into future research on the eco-design of BIPV in the conclusion section.

2. Data and method

LCA is a well-developed method, with the first international guidelines for conducting LCA studies dated back to 1997 [39]. It quantifies and evaluates the environmental impacts of product or service from the raw material extraction for making the product till the end of its life [40]. LCA covers the complete life cycle of a product, therefore the application of LCA helps to avoid the burden shifting or transferring the impacts from one stage during the life cycle to another stage. With LCA, all the environmental impacts are taken into consideration, which avoids neglecting of any uncommon impact categories, or missing of any indirect impacts. These two features of LCA make it a holistic method and a fitting tool for eco-assessment. Besides, by conducting

Table 1
Key aspects of LCA based eco-design guidelines in the literature.

Paper	Technology	Functional unit	Indicator
[30]	Multi-crystalline silicon (mc-Si) BIPV with and without phase change material	m^2	18 midpoint impact categories of ReCiPe
[35]	mc-Si BIPV	system	Energy and GHG indicators
[28]	Crystalline (c-Si) and amorphous (a-Si) BIPV with heat recovery unit	system	Energy indicators
[29]	Free standing and building integrated PV/ thermal (BIPV/T)	m^2, system and year	Energy and GHG indicators
[33]	Building integrated concentrated PV (BICPV) with single-crystalline (sc-Si) PV	system	11 indicators of Eco-Indicator 99 and EPS 2000 (Environmental Priority Strategies)
[24]	Hybrid PV/T façade based on silicon and non-silicon	not available (n/a)	Energy and GHG indicators
[36]	Dielectric based BICPV	kWh	Energy and GHG indicators
[27]	Adaptive BIPV facade	kWh and system	Six major midpoint impact indicators of ReCiPe
[25]	mc-Si, a-Si and CIGS BIPV	m^2	Carrying capacity
[37]	sc-Si BIPV	kW and kWh	One endpoint indicator of ReCiPe and GHG
[32]	Semi- transparent BIPV window	n/a	Energy, GHG and six other environmental impacts of Chinese abiotic resource depletion, CML 2002 and IMPACT 2002+
[31]	Textile envelope integrated flexible PV and PV glazing sunshade	m^2	GHG and cost
[26]	c-Si and perovskite BIPV, slanted roof and façade	kWh	Cost, GHG emissions, CED, fossil depletion and other impacts of ILCD (International Reference Life Cycle Data System)
[38]	mc-Si BIPV	kWh	Energy and GHG indicators
[34]	Floating, bifacial ground mounted, BIPV and conventional PV	kWh	15 indicators of PEF (Product Environmental Footprint) except for ecotoxicity

comparative LCAs, scenario analyses, and environmental hotspot identifications, LCA can be applied for eco-improvement.

In this study for the case of BIPV, the application of LCA becomes crucial as this technology generates renewable electricity and causes modest environmental impacts during its operation. By including all impacts from both upstream processes such as mineral and metal extraction for producing the mounting system, and downstream processes such as waste treatment and recycle of decommission modules, the consideration of its life cycle environmental impacts will make a fair comparison of this technology and other technologies of the energy sector as well as the building sector.

Life cycle thinking approach can be applied for all three aspects of sustainability. While the conventional LCA considers the environmental impacts, life cycle costing and social life cycle assessment are applicable for economic and social aspects, and life cycle sustainability assessment can be used as an overarching general framework encompassing all sustainability perspectives. All these methods share the common framework of 'life cycle thinking', meaning that they consider the impacts for its whole life cycle.

This study will apply the attributional approach for LCA for environmental impacts, in which all inputs and outputs of a product system are attributed to the functional unit. This is done by linking the unit processes of the system to that functional unit within a defined system boundary [41]. Apart from environmental impacts, the economic aspect is studied by applying LCC.

The ISO14040 and ISO14044 standards [42,43], for conducting an LCA study, with four steps of goal and scope definition, inventory analysis, impact assessment and interpretation will be followed. During the first step, the goal and scope need to be defined, providing such information as the goal of the study, intended applications of the study, product system, function and functional unit, system boundary, data requirement, allocation rule, assumptions and life cycle impact assessment method. The second step relates to life cycle inventory analysis, which is an iterative process consisting of three sub-steps: collecting data, calculating data and determining reference flows and emissions. Life cycle impact assessment is the third step, aiming at understanding and estimating the size and significance of the potential environmental impacts of a product system over the life of the product. It consists of two compulsory sub-steps: classification and characterization, and some optional sub-steps: normalization, weighting and grouping. The final step is interpretation which presents the results of the inventory analysis and the life cycle impacts. During this step, dominance analysis, hotspot identification, uncertainty analysis and sensitivity analysis may be performed to further understand the obtained results and evaluate the effects of the most important assumptions and selected methods.

Besides, the study refers to the guidelines of IEA for LCA on solar PV [44,45] and Product Environmental Footprint (PEF) of the European Commission [46]. For LCC, the method is based on cost and benefit analysis [47]. The specific methods applied on BIPV will be further described in the following sub-sections.

2.1. Technology description

The studied BIPV module is a glass-glass PV module, being suitable for building integration. Each of the glass layer is 4 mm thick, and the total thickness of the module is 9.8 mm. The PV module is 72 mono-crystalline silicon type, with cell dimension of 156 x 156 mm. The power of module is 315 Wp. The module dimension is 1.998 m^2 (1325 mm x 1508 mm), with the total weight of 55.02 kg. This module lasts around 25 years. The BIPV module is currently studied and demonstrated in Bolzano, under the NEST Spoke 1 project. Similar modules are installed in Firenze, with the installed capacity of 17.5 kWp for both roof and window installations. The examples of roof and window installations of the studied modules are illustrated in Fig. 1.

2.2. Goal and scope definition: functional unit and system boundary

All the environmental impacts of the BIPV panels are quantified from cradle to grave i.e. from the material extraction, cell production, panel assembly and installation, electricity generation and end-of-life treatment of decommissioned panel. The transportation stage is also included. The selected functional unit is 1 kWh of electricity being generated by the panels. The same functional unit is applied for life cycle costs, with consideration of manufacturing costs only. There is no cut-off or allocation procedure being applied in this study.

2.3. Scenarios of technology development and fabrication cost

The final goal of the study is to propose eco-design measures for emerging BIPV modules; therefore, several scenarios has been assessed, focusing on three aspects (1) the transmittance (and relevant PCE) of the cells, (2) cells' materials such as silicon and perovskite and (3) end-of-life management strategies including disposal and recycling of module. Different from the traditional solar PV modules, the BIPV modules requires the aesthetic value when being integrated into the living area. For common solar PV, no transmittance is needed, in this case the PCE can be exploited at maximum. However, for BIPV modules, sometimes opaque module is needed for roof installation. In some other cases, the window installations require higher transmittance, being similar to typical windows. In this case, the PCE reduces, being traded-off for the high transmittance. Furthermore, the solar PV panel's efficiency is

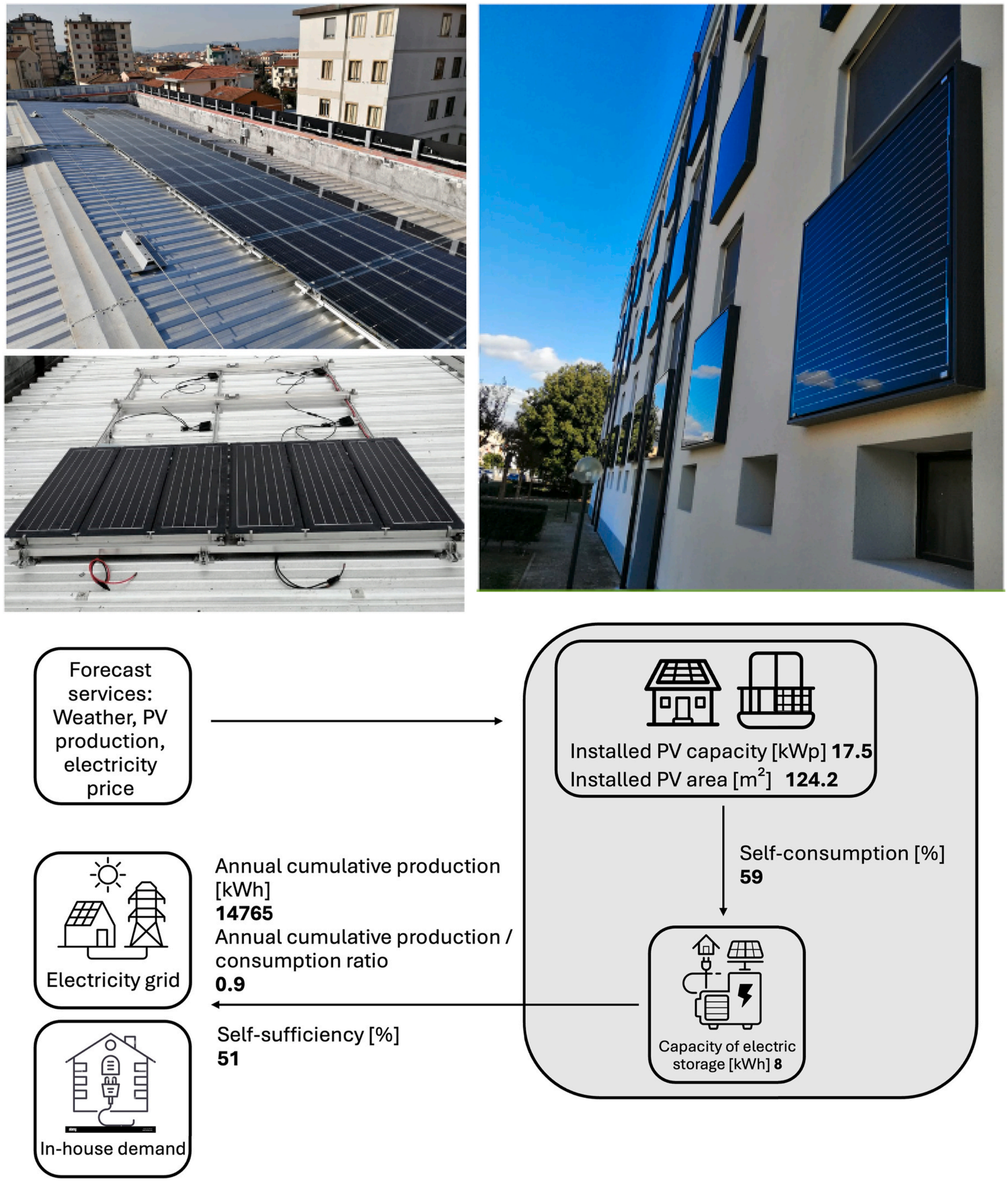

Fig. 1. Examples of roof and window installed BIPVs in Firenze, top right: rooftop BIPV, top left: window BIPV [48], and bottom: 2D drawing of the system.

limited by the Shockley-Queisser limit, which leads to the study of new materials and new structure for solar PV and BIPV in particular. The studies on new materials such as perovskite and comparison of new and conventional material (e.g. silicon) is essential to test the new materials and to identify any potential for the new materials enter the market from different point of views, covering technical opportunities, and environmental impacts/benefits. Similarly, the cost scenarios aim at examining various glasses and back sheets from the economic perspectives. Regarding the end-of-life management strategies, the decommissioned BIPV module are required to be recycled and recovered under the Waste from Electrical and Electronic Equipment (WEEE) directive [49]. Therefore, the end-of-life treatment, whether its contribution is large (or small) should be studied. This is even more important in the case of new modules such as perovskite based BIPV, as the study on end-of-life treatment of new modules is limited and there are concerns on toxicity of the cells containing toxic materials, e.g. lead. The detail of scenarios is presented in Table 2.

The control parameters of these scenarios include transmittance, lifetime of the modules, materials for the cells and the end-of-life management strategies. These control parameters are selected due to their difference in technical requirement of common PV and BIPV modules (e.g their transmittance and aesthetic value), the need of new material and structure for solar PV sector to increase the modules' efficiency and reduce their environmental impacts. The last control parameter on the recycling strategy of the module is selected due to the policy requirement on recycling the decommissioned PV modules.

Table 2
Scenario details for eco-design of emerging BIPV modules.

Scenario	Technology	Location (annual solar radiation)	Transmittance (PCE)	Lifetime	End-of-life treatment
S1	SSC, Roof installation, 315 Wp	Bolzano (1600.19 kWh/m^2/yr)	No transmittance (23 %)	25 yrs	Disposal
S2	SSC, Façade installation, 17.5 kWp	Firenze (1494.50 kWh/m^2/yr)	High transmittance (9 %)	25 yrs	Disposal
S3	SSC, Façade installation, 315 Wp	Bolzano (1600.19 kWh/m^2/yr)	High transmittance (10 %)	25 yrs	Disposal
S4	SSC, Façade installation, 315 Wp	Bolzano (1600.19 kWh/m^2/yr)	Opaque, 30 % transmittance (15 %)	25 yrs	Disposal
S5	PSC, Façade installation, 315 Wp	Bolzano (1600.19 kWh/m^2/yr)	Opaque, 30 % transmittance (18 %)	15 yrs	Disposal
S6	PSC, Roof installation, 315 Wp	Bolzano (1600.19 kWh/m^2/yr)	No transmittance (27 %)	15 yrs	Disposal
S7	S1				Recycle module and recover, glass, aluminium and copper for fabricating the recycled cells
S8	S2				
S9	S3				
S10	S4				
S11	S5				
S12	S6				
C1	S1, glass on glass module with sc-Si PERC cells				
C2	S2, glass on glass with extra clear and lacobel glass and IBC Maxeon cells				
C3	S3, glass on backsheet with float coloured and IBC Maxeon cells				
C4	S4, glass on backsheet with extra clear glass and IBC Maxeon cells				
C5	S5, glass on glass with perovskite solar cells				
C6	S6, glass on glass with perovskite solar cells				

2.4. Inventory analysis: data and assumptions

As recommended in the ISO standards, the data for foreground processes should be primary, while the data for background process might be taken from relevant database. This study applies the same principle for foreground process (the data for module assembly and installation) on-site data, provided by the NEST Spoke 1 project's partners. Manufacturing of the PSC is considered as foreground process with on-site data, being provided by the NEST project partners, while manufacturing of the SSC are background process with data being taken from the most updated and reliable life cycle inventory (LCI) datasets of IEA PVPS Task 12 [50]. The data for recycling of PV modules are referred from reports of IEA [51,52]. The data for other background processes (e.g. the manufacturing of other components) are taken from Ecoinvent database [53]. All the data sources are the most reliable, updated and popular for LCA studies in general and LCA of solar PV in particular. Table 3 provides the LCI data of assembling PV module, fabricating PSC and other background processes.

There are several assumptions regarding the transportation of the solar cells and electricity consumption. Regarding transportation, no transportation is needed for BIPV assembly and installation, as the BIPV is installed in the laboratory of the NEST project partner. However, for fabricating the module, different assumptions are made. For the SSC, the EU average market shares along with the relevant need for transportation are applied, i.e. 83.9 % of PV cells are transported from Asia Pacific and the remaining of 16.1 % comes from domestic supply [50]. For PSC, materials are transported from the local storage of the suppliers to the laboratories of the NEST project's partners.

Moreover, it is assumed that the production and installation (if any) occur in Italy, i.e. the Italian grid mix will be applied for the use of electricity during these two stages. In terms of costs, it is assumed that all the incurred costs are in EUR. In cases where the costs for materials are quoted in other currency, the exchange rate of the European Central Bank will be applied. The cost data is provided by the laboratories of the NEST project partners, which is sourced from the suppliers of the materials. It is assumed that all consumed materials are measured in weight to match with the Ecoinvent database. In case the materials are bought in piece, or volume, the conversion based on their density will be applied, for matching life cycle environmental impact assessment and LCC quantification.

Table 3
LCI of panel assembly and PSC fabrication.

Major components/ materials	Unit	Value	Source of data
For 1 m^2 of panel assembly and installation			Data from the laboratories of the NEST project's partners
PV glass	kg	2.00E+01	
Solar cells	m^2	8.77E-01	
Encapsulant	kg	1.65E+00	
Copper connector	kg	2.20E-01	
Wire and connectors	kg	2.50E-01	
For 1 cm^2 of PSC fabrication			
Fluorine Tin Oxide glass	g	8.70E-01	
Acetone	g	2.52E-01	
Isopropanol	g	2.50E-01	
Silver	g	2.00E-02	
Titanium diisopropoxide bis	g	9.50E-03	
Acetylacetonate	g	6.20E-03	
Ethanol	g	1.13E-01	
Dimethyl sulfoxide	g	4.40E-02	
Formamidinium bromine	g	4.96E-03	
Lead bromide	g	1.47E-02	
PTAA	g	5.33E-03	
Anhydrous toluene	g	3.00E-02	
Indium tin oxide	g	8.00E-04	
Nitrogen gas	kg	9.80E-03	
Electricity consumption	kWh	6.99E-01	
Transportation	tkm	8.14E-04	Assumption
Background processes			
Manufacturing of SSC			[50]
Recycling of BIPV module			[51,52]
Manufacturing of other components and processes (electricity, transportation, inverter, etc.)			[53]
Electricity, medium voltage {IT}			
Transport, freight, lorry 3.5–7.5 metric ton, EURO 5 {RER}			
Inverter 2.5 kW {GLO}, Inverter 0.5 kW {GLO}			

2.5. Indicators and equations

Currently, there is a wide range of life cycle environmental impact assessment (LCIA) method and relevant indicators such as ReCiPe [54], indicators of IEA PVPS Task 12 for LCA guideline [44], and European PEF for midpoint environmental indicators [46]. The selected LCIA method is PEF, which is suitable for assessing the environmental impacts of solar energy technologies in European context [55,56].

The PEF method covers 16 indicators: climate change (GWP), ozone depletion (ODP), human toxicity, cancer (HT-c), human toxicity, non-cancer (HT-nc), particulate matter (PMF), ionizing radiation (IR), photochemical ozone formation (PCOF), acidification (AP), eutrophication, terrestrial (EP-t), eutrophication, freshwater (EP-fw), eutrophication, marine (EP-m), ecotoxicity, freshwater (ET-fw), land use (LU), water use (WU), resource use, minerals and metals (EU-m) and resource use, fossils (RU-f) [46].

LCC method is based on cost and benefit analysis, with one indicator of the LCOE, being quantified for 1 kWh of electricity generated from BIPV modules.

Equation (1) presents an example of quantifying life cycle environmental impacts:

$$Imp_j = \sum_{1}^{n}\left(\sum\nolimits_{1}^{m}\left(\sum Am_i{*}CF_{i,j}\right)\right) \tag{1}$$

In which:

Imp_j is the life cycle impact j

n is the life cycle stages

m is process.

Am_i is the amount of air emissions of substance i.

$CF_{i,j}$ is the characterization factor of substance i to the impact j

PEF recommends two life cycle stages of raw material acquisition, pre-processing, module manufacturing and distribution. This study is conducted on lab-scale and pilot BIPV modules; therefore, distribution stage is not available. Besides, the end-of-life stage with two options of disposal and recycle the BIPV modules is considered in the study.

Equation (2) represents an example of cost calculation:

$$LCC = \sum_{1}^{n}\left(\sum\nolimits_{1}^{m}\left(\sum Am_k{*}uCost_k\right)\right) \tag{2}$$

In which:

LCC is life cycle cost, measured in Eur

n is the life cycle stages

m is process.

Am_k is the amount of input consumed or output recycled or treated k

$uCost_k$ is the unit cost of input or output k

Due to the limitation of data, this study quantifies the costs during manufacturing stage only. Besides no externality is included in the calculation.

Equation (3) represents an example of hotspot identification:

$$HS = \frac{Imp_{j,c} \times 100}{Imp_{j,p}} \tag{3}$$

In which:

HS is the contributions of different components to the total impact of the product, measure in percentage (%)

$Imp_{j,c}$ is the life cycle impact j of component c

$Imp_{j,p}$ is the life cycle impact j of product p

3. Life cycle impact assessment and interpretation: results

The results cover five important points of the eco-design of BIPV, including (1) the links between transmittance, PCE and environmental impacts, (2) the contribution of components and the selection of materials to the environmental impacts, (3) the role of end-of-life treatment in reducing environmental impacts, (4) the economic feasibility of the BIPV module and cost of electricity generated by the modules, and (5) proposal of eco-design measures for BIPV. The first four pieces of results correspond to the scenarios, while the last pieces of results are the practical measures for eco-design of BIPV which are obtained from the analysis of the first four pieces of results. The eco-design of BIPV is presented in Fig. 2.

3.1. Transmittance, PCE and environmental impacts

The life cycle impacts are calculated for a grid-connected rooftop module installed in Bolzano over it 25 years of lifetime in Scenario 1 (S1). Only electricity generation is taken into account, without any consideration of thermal production of BIPV. The GWP of the module is at 2.41E-02 kg CO_2 eq. Comparing to the PV systems installed in Italy, with the average carbon footprint at 2.76E-02 kg CO_2 eq per kWh for optimized S-facing panel and the mean value of BIPV in EU at 3.58E-02 kg CO_2 eq per kWh [57], the carbon footprint of BIPV in this study is slightly lower.

Meanwhile, the GWP of window installation module installed in Firenze in Scenario 2 (S2) nearly triples that of S1 module, at 6.73E-02 kg CO_2 eq. Similarly, other environmental impacts of S2 module are significantly higher than those of S1 module, from 2.8 to 3.8 times.

The difference is lowest among ODP, GWP and RU-f. For example, the GWP of S2 is 2.8 times higher than that of S1, at 2.42E-02 kg CO_2 eq per kWh of electricity. Meanwhile the difference is highest among HT-nc, and RU-m. For example, the RU-m of S2 is 5.74E-06 kg Sb eq, which is 3.5 times higher than that of S1, 1.66E-06 kg Sb eq. The difference between the environmental impacts of these two modules mainly originates from the lower solar radiation in Firenze and lower PCE of window-installed module, which has been traded-off for its high transmittance, compared to rooftop module in Bolzano, with a small contribution of energy used for rooftop and facade installations, as well as the installed capacity of system at 315 Wp and 17.5 kWp.

Comparing with other BIPV windows or façade in the literature, the GWP of BIPV in the scenario S2 is considerably lower, being as half of the average GWP of dielectric based BICPVs, at 142 gCO_2eq [36] and nearly five times lower than that of adaptive solar façade without taking into account of carbon offset due to energy savings for heating, cooling and lighting, at 331 gCO_2eq [27]. The GWPs of the studied S2 module and the literature are considerably difference due to the fact that these modules, and the scope of the quantified indicators are different. Table 4 presents the life cycle impacts of the rooftop module installed in Bolzano and the façade module installed in Firenze.

The life cycle environmental impacts largely depend on the transmittance and PCE of the module. The PCE is highest in case of rooftop installation (S1), which delivers the lowest environmental impacts. When the transmittance increases and the PCE decreases, the environmental impacts gradually increase in scenarios S2, S3, S4 for façade installation categories (as presented in Fig. 3). Comparing the highest and lowest environmental impacts of scenarios S2 and S1 respectively, indicates the differences are around 2.8 to 3.8 times as mentioned above. Meanwhile the difference between consecutive scenarios, e.g. between S2 and S3, between S3 and S4, and between S4 and S1 are around 1.5 times for most of the impact. Specifically, the environmental impacts of S3 are 1.5 times larger than those of S4 for all impact categories because these two scenarios are similar in most aspects, except for the transmittance and corresponding PCE. In case of changing both PCE and types of installation, e.g. façade installation in S4 and roof installation in S1, the difference among corresponding impacts ranges from 1.5 to 1.7 times, indicating that types of installation have a smaller contribution to the environmental impacts compared to PCE. Finally, environmental impacts of S2 modules are larger than those of S3 module from 1.2 to 1.6 times, depending on the impact categories, indicating that increasing the installed capacity (from 315 Wp and 17.5 kWp) brings some

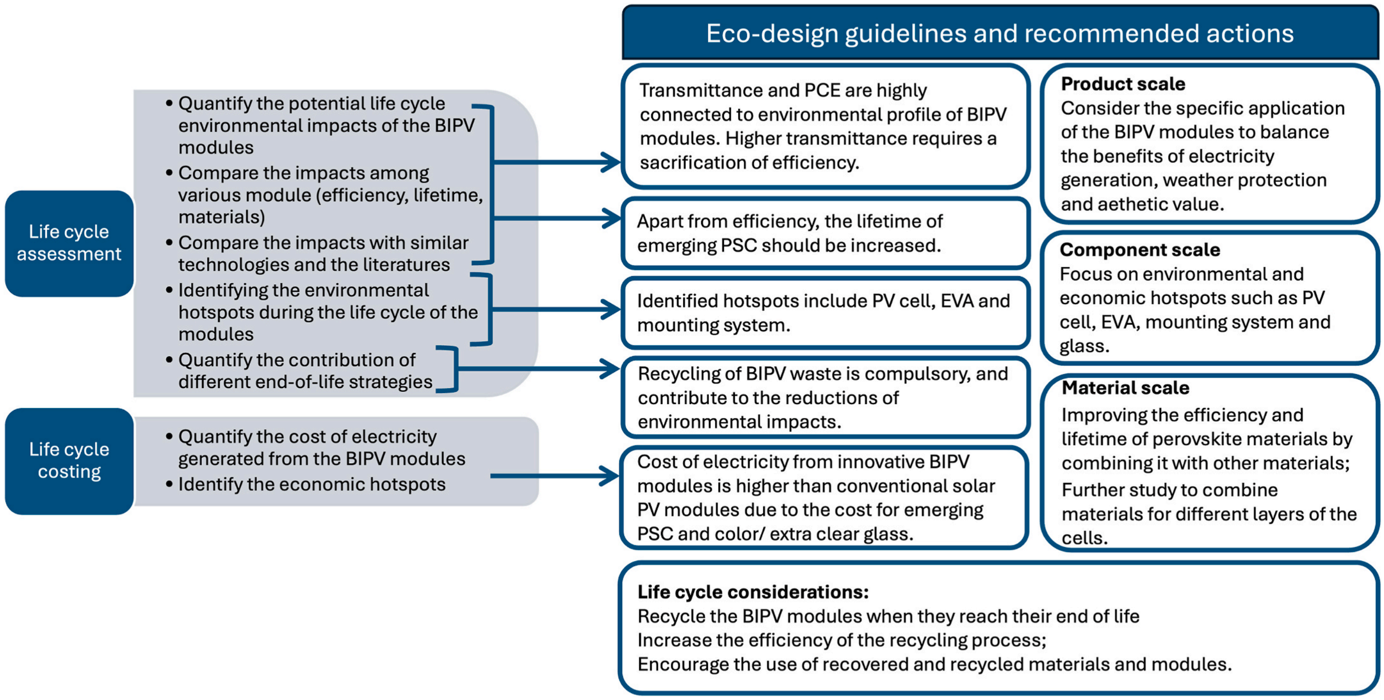

Fig. 2. Eco-design of BIPV.

Table 4
Life cycle impacts of BIPV modules.

Impact	Unit	BIPV rooftop, Bolzano (S1)	BIPV facade, Firenze (S2)
AP	mol H+ eq	1.98E-04	6.52E-04
GWP	kg CO_2 eq	2.41E-02	6.73E-02
ET-fw	CTUe	3.45E-01	1.04E+00
PMF	disease inc.	1.71E-09	5.00E-09
EP-m	kg N eq	5.63E-05	1.62E-04
EP-fw	kg P eq	1.62E-05	5.36E-05
EP-t	mol N eq	3.20E-04	9.52E-04
HT-c	CTUh	3.28E-11	1.02E-10
HT-nc	CTUh	1.29E-09	4.90E-09
IR	kBq U-235 eq	2.42E-03	7.62E-03
LU	Pt	1.24E-01	3.62E-01
ODP	kg CFC11 eq	1.20E-09	3.30E-09
PCOF	kg NMVOC eq	1.02E-04	2.97E-04
RU-f	MJ	2.92E-01	8.22E-01
RU-m	kg Sb eq	1.66E-06	5.74E-06
WU	m^3 depriv.	2.25E-02	6.35E-02

Notes: Acidification potential: AP, Global warming potential: GWP, Ecotoxicity – freshwater: ET-fw, Particulate matter formation: PMF, Eutrophication potential – marine: EP-m, Eutrophication potential – freshwater: EP-fw, Eutrophication potential-terrestrial: EP-t, Human toxicity – cancer: HT-c, Human toxicity – non cancer: HT-nc, Ionizing radiation: IR, Land use: LU, Ozone depletion potential: ODP, Photochemical ozone formation: PCOF, Resource use - fossil: RU-f, Resource use – mineral and metal: RU-m, Water use: WU.

offsetting affects for the lower solar radiation (of Bolzano and Firenze).

The BIPV systems can be utilized for two applications, being installed on rooftop or façade. In case of rooftop BIPV, the environmental impacts are similar to those of PV, thanks to the high PCE of the system. In case of being integrated into the building as window or façade, the PCE is traded-off with the transmittance and aesthetical value. As a result, the environmental impacts tend to increase and are higher than the conventional PV cells. For the eco-design of BIPV module, it is importance to select the suitable products for different applications, and correspondingly the materials for that product. Besides, the design of BIPV module, especially for the window installation, should focus on materials that can balance the transmittance, aesthetic values as well as the efficiency of the module.

3.2. Components, materials and environmental impacts

Analysis on the contribution of different components to the life cycle impacts per kWh from cradle to grave indicates that the PV cell is the largest contributor to most of the impacts categories (see Fig. 4). It accounts for 71 % of WU, 64 % of EP-m, 49 % of IR, 45 % of ET-fw. It is also the top contributor of some other impacts, with a smaller share, for example 31 % of GWP, 32 % of EP-fw, 30 % of EP-t, 28 % of PCOF and 34 % of RU-f. EVA is the largest contributor to ODP (55 %). Mounting system is the largest contributor to PMF (26 %) and HT-c (31 %). Electricity installation is the largest contributor to HT-nc (53 %), and RU-m (40 %). The end-of-life treatment (including waste treatment of panel and cell production process and the recycling of the used panel) accounts for an insignificant share of the life cycle impact.

In such case, the eco-design of BIPV module should focus on the PV cells, for reducing several environmental impacts such as ET-fw, GWP, EP and RU-f. At the same time, other components such as EVA, mounting system, and process such as electric installation should not be neglected during the design of the module.

To examine the role of materials for PV cells in eco-design of the BIPV modules, two scenarios with modules made from PSC (S5 and S6) are conducted. By using PSC in replacement of SSC, the PCE increases while the lifetime of the cells decreases due to the instability of perovskite material. In this case, the environmental impacts of perovskite based BIPV module are much higher than those of silicon based BIPV module (as presented in Fig. 5). The environmental impacts of perovskite based BIPV module are from 1.7 to 32 times higher than those of silicon-based materials for window installation (S5 vs. S2), and from 4 to 60 times for rooftop installation (S6 vs S1). The lowest difference is among HT-nc, at 1.7 times for window installation and ET-fw, at 4 times for rooftop installation. The highest difference lies in WU, for both installations. The GWP of perovskite-based BIPV module is 10 times and 19 times higher than that of silicon-based module, for window and rooftop installation, respectively.

The GWP of silicon based BIPV (S1) in this study is 24.1 gCO_2eq per kWh, which is very close to the average carbon footprint of BIPV in Italy,

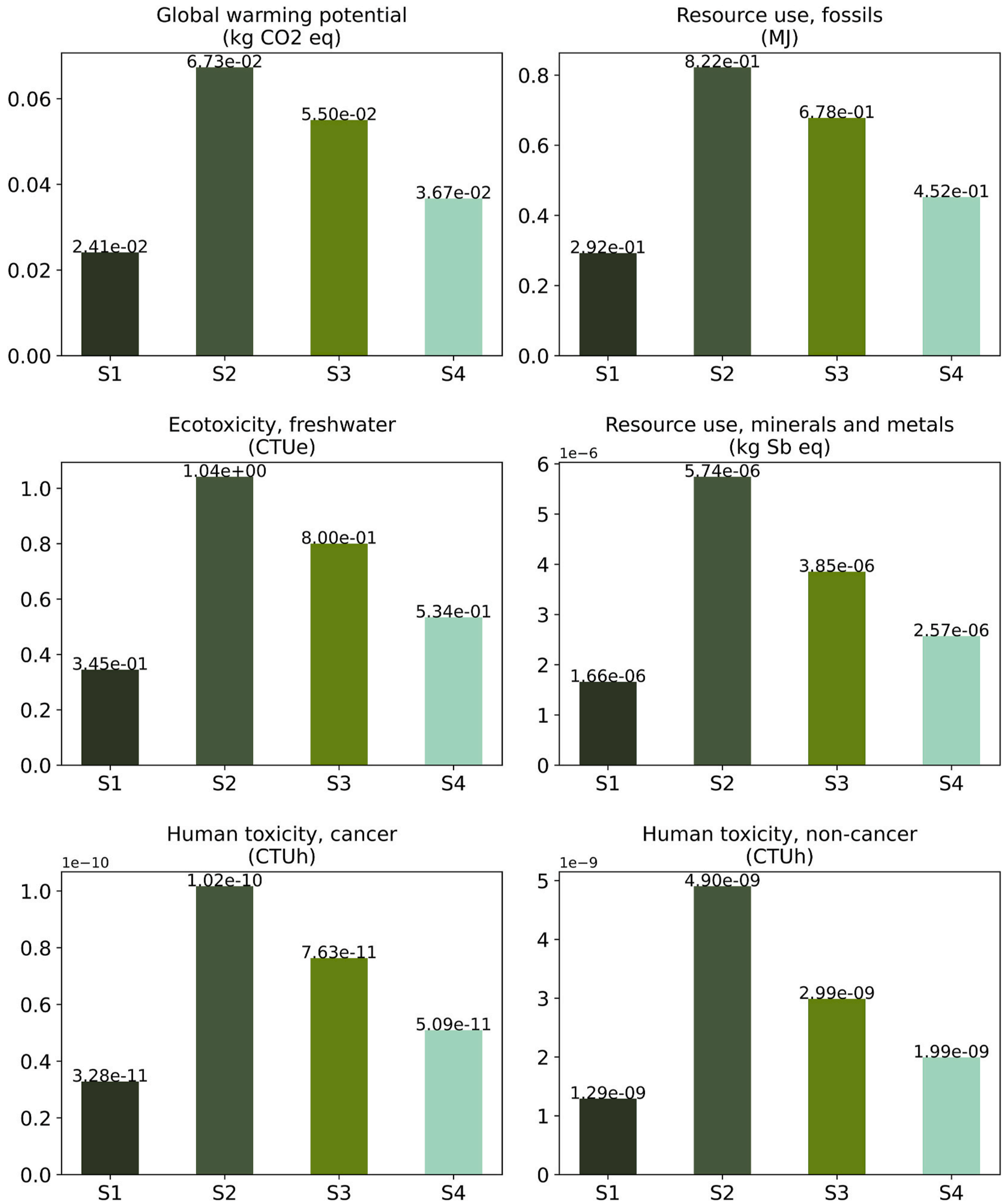

Fig. 3. Life cycle impacts of BIPV module.

at 27.6 gCO_2eq per kWh for optimized S-facing panel, lower than the mean value of BIPV in EU at 35.8 gCO_2eq per kWh [57]. The similarity indicates the representativeness of S1 BIPV in this study and can be explained by the selected datasets (IEA datasets) and technology (SSC without transmittance and with maximum PCE) among two studies. However, in cases of perovskite material, the GWP increase to 460 gCO_2eq per kWh, which is now nearly 13 times higher than the EU average of silicon based BIPV.

It should be noted that SSC is a mature technology, with efficient and industrialized manufacturing process, while PSC is currently under its early development, and being studied at lab scale. The production scale of the cells may contribute a small part to the difference in their environmental impacts of the two modules. However, it is undeniable that at the current stage of development, the higher PCE of perovskite cells can not compensate for its short lifetime, considering the environmental impacts of BIPV module per kWh of electricity being generated.

Therefore, for the eco-design of BIPV module, apart from the efficiency of solar material, it is encouraged to extend the lifetime of emerging PV cells such as PSC. Only by this way, the substitution of new materials can compete with the traditional ones in both energy and environmental terms.

3.3. End-of-life treatment and environmental impacts

According to EU policy, it is compulsory to recycle the PV panel [49, 58]. At the same time, there is a concern on toxicity coming from lead used in PSC. Therefore, though the contribution of end-of-life treatment of PV module is inconsiderable, two end-of-life management strategies (in scenarios S6, S7, S8, S9, S10, S11 and S12) are proposed to compare their contributions on the life cycle impacts. The main environmental impacts of S7, S8 and S12, being compared to S1, S2 and S6 are presented in Fig. 6.

Recycling helps to reduce most of impact categories such as GWP, ET-fw, HT-c, HT-nc, RU-f, RU-m and etc. The reduction ranges from 1 %

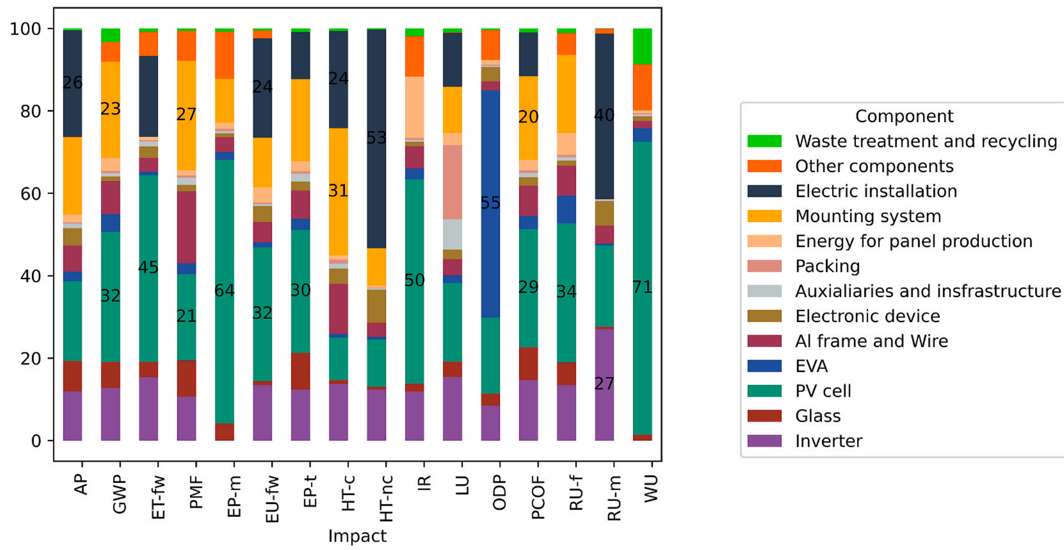

Fig. 4. Share of impacts by components of BIPV rooftop.

to 23 %, with the highest reductions in PMF at 23 % in case of recycling the rooftop installed BIPV module, and 22 % in case of recycling façade installed BIPV module. Other impacts which have relatively large reductions include HT-c (from 10 % to 11 %), AP, EP-t and PCOF (from 8 % to 9 %). Reductions in RU-m and EP-fw are the lowest, at 1 %. However, the eco-design measure of recycling has some environmental trade-offs. While it reduces most of impact categories, it causes an increase in IR and WU. Specifically, recycling causes an increase by 8 % in IR of rooftop module, and by 13 % in WU of rooftop module and 14 % in WU of façade module.

Recycling has a negligible impact on perovskite modules, with the reduction of impacts being less than 5 %. Besides, there is no identified trade-off from the recycling of perovskite module, meaning that this eco-design measure causes either unnoticeable change or reduce all the environmental impacts in this type of BIPV module.

3.4. Fabrication cost of emerging BIPV module

Costs for electricity generated from BIPV module are at 0.01 EUR per kWh for rooftop installation and 0.37 EUR per kWh for window installation (as presented in Table 5). The cost of reference case C1 for rooftop installation lies in the range of literature for LCOE of small solar PV systems in Germany, from 0.0065 to 0.014 EUR per kWh [59]. Besides, the costs of window-installed cases (C2, C3 and C4) are similar to those of BIPV façade system in Norway from 0.11 to 0.35 EUR per kWh [60].

The components including PV cells, glass and inverter contribute a large part of the total cost per kWh, from 91 % to 99 %. The use of energy for fabricating, installing and transporting the module accounts for small parts of the total cost. The costs of electricity generated from perovskite-based BIPV module (C5 and C6) are much higher than that of silicon-based module (C1), due to the significant share of cost for PSC fabricated at lab scale. Besides, the costs of electricity generated from window-installed module (C2, C3 and C4) are relatively higher than that of rooftop module (C1) due to the high price of colour glass and extra clear glass for transmittance and aesthetic value.

3.5. Eco-design guidelines

The eco-design guidelines for emerging BIPV modules cover the following main points.

- On the product scale, it is necessary to select the suitable products for different applications, and correspondingly the materials for that product. While the rooftop BIPV does not need the high transmittance, the window application requires higher transmittance and aesthetic values. In such case, the PCE of window application is lower than that of rooftop installation. At the same time, the aesthetic requirement of BIPV window cause a higher cost for better quality glass. As results, the environmental impacts per kWh of electricity generation as well as the LCOE of window installation are higher than those of rooftop installation. The eco-design of emerging BIPV modules, therefore, should take into consideration of specific applications of the product, and tailor-made materials for PV cells as well as other components accordingly.

In case the BIPV modules are installed on the rooftop of the building, it is recommended to use the conventional silicon-based solar PV module. These modules deliver high PCE, consequently generate the maximum amount of electricity. For fully integrated of BIPV modules on the rooftop, frameless PV laminates may be installed and integrated with special mounting system to ensure the waterproof function of the roof [61]. For the similar purpose of "fully integrated", PV tiles may be utilized in replacement of traditional tiles, or thin-film layers can be tailor-made to cover a rigid substrate as requirement of the customers [61].

Sometimes, the BIPV modules require the high transmittance, for examples agrivoltaics on the roofs and walls of glass houses, and PV modules on the roofs, façade for aesthetic purposes, and BIPV windows. In such cases, colour glass, perovskite material for absorber layer, and combinations of materials for electron transport layer are recommended.

- On the component scale, the eco-design should focus on environmental and cost hotspots, such as PV cell, EVA, mounting system, glass. PV cell is the largest contributor for most of environmental impacts, while EVA and mounting system are the main contributors for ODP, PMF and HT-c. In term of cost, colour glass is the main cause of high cost of BIPV window. Besides, the PSC is expensive due to its lab-scaled production.
- On the material scale, it is encouraged to study innovative materials so that it can balance the transmittance, aesthetic values as well as the efficiency of the BIPV module. At current development stage, the replacement of perovskite for silicon does not bring energy and environmental benefits. The change into new materials such as perovskite can only be feasible if the efficiency and lifetime of PSC are improved and extended.

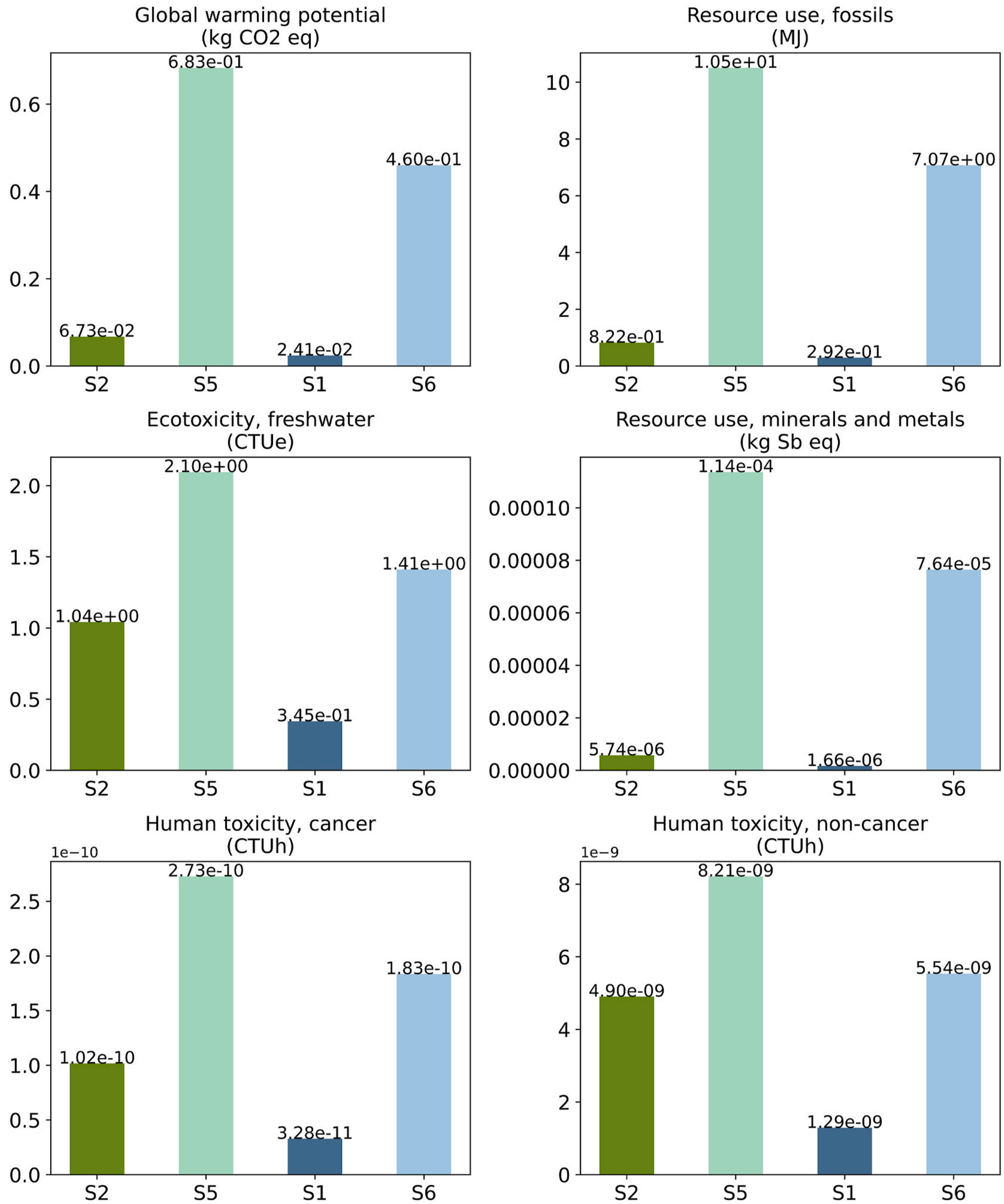

Fig. 5. Materials and environmental impacts.

In order to improve the efficiency and lifetime of the perovskite cells, a mixture of solutions is needed, being relevant to the material of each layer of the cells, the combination of materials, the structure of the cells and even the fabrication process. A recent literature proposed the two terminal perovskite and silicon tandem cells being fabricated by mechanically stack-up, with tin oxide on top of titanium dioxide doped with carbon as electron transport layer, which achieve the PCE of 31 % [62]. In other cases of building applications, the transmittance is increased by using ionic liquid in inorganic cesium lead bromide perovskite, obtaining the PCE of 6.11 % with visible transmittance value of 58 % [63], or utilizing the indium tin oxide/silver/indium tin oxide multilayer for the visible transmittance value of 87 %, while enhancing the solar energy efficiency under high temperature conditions [64].

- Considering that recycle of decommissioned BIPV module is compulsory, it is suggested that the recycling process need to be further study. This will increase the efficiency of recycling process itself, as well as increasing the amount and quality of recovered materials that can be used in the recycled modules.

Table 6 presents a summary of eco-design guidelines with recommended actions and benefits of implementing these eco-design measures.

The successful implementation of these eco-design measures would require the cooperation of various stakeholders. While the first three eco-design measures on product, component and material scales are more relevant to BIPV developers, including business managers, engineers, environmental managers and designers, the last measure involves both manufacturing industry and other stakeholders along the BIPV supply chain, such as the waste treatment and recycling companies. The role of policy makers is also undeniable in encouraging the research and development of new materials for BIPV, with consideration of technical improvement and environmental sustainability, going beyond the manufacturing processes to cover the whole life cycle of the technology.

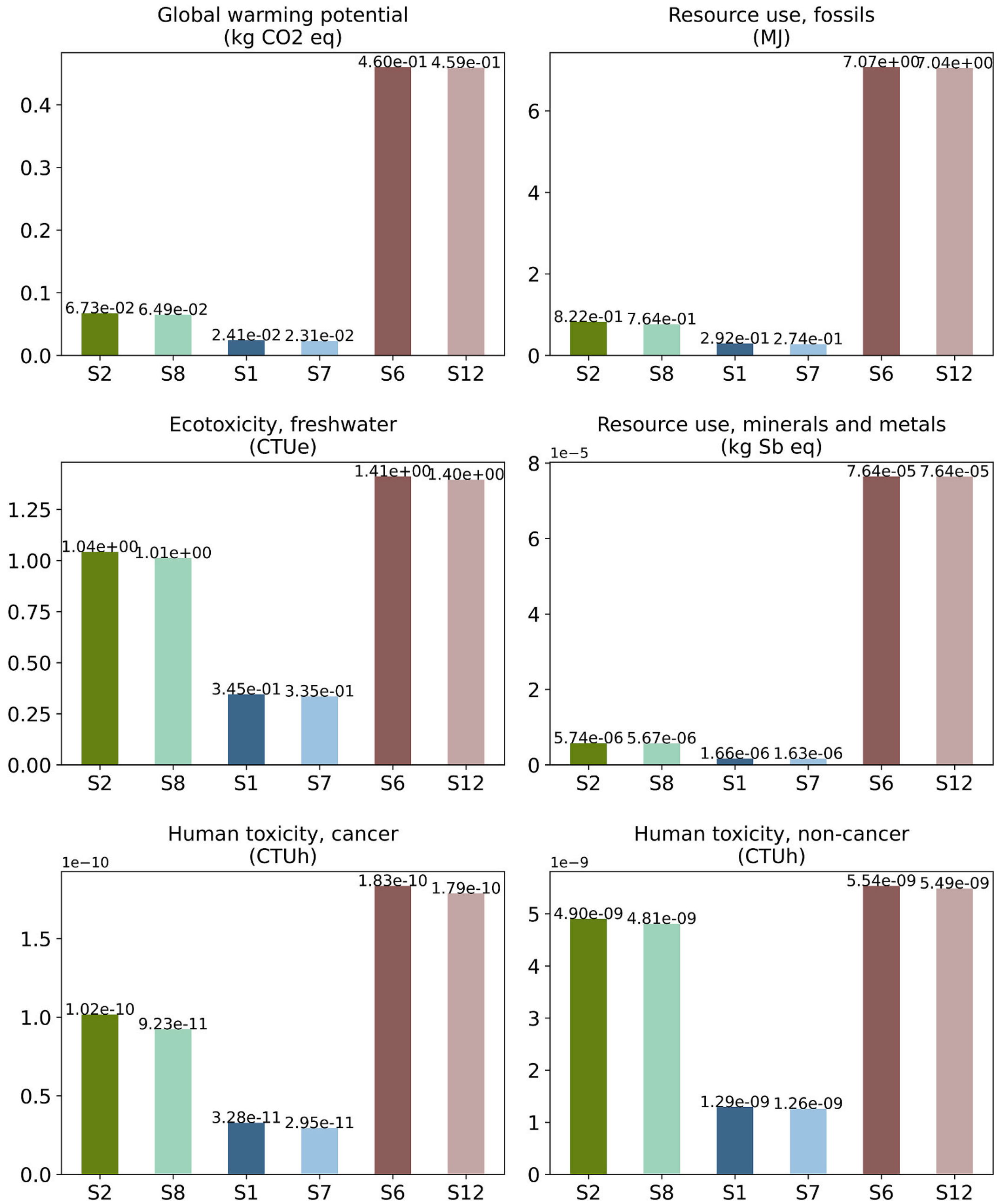

Fig. 6. EoL treatment and environmental impacts.

Table 5
Levelized cost of electricity.

Cost components	C1	C2	C3	C4	C5	C6
Material	5.63E-03	3.71E-01	9.13E-02	5.76E-02	2.84E+00	1.91E+00
Energy	2.07E-04	5.84E-04	4.82E-04	3.21E-04	1.92E-01	1.29E-01
Transport	3.34E-04	9.40E-04	7.76E-04	5.17E-04	9.66E-04	6.50E-04
Lab equipment					1.47E+02	9.91E+01
Total cost without lab equipment	0.01	0.37	0.09	0.06	3.03	2.04
Total cost	0.01	0.37	0.09	0.06	150.28	101.12

As mentioned before, the implementation of eco-design measures involves various stakeholders, which is also a challenge for the development of BIPV. While the engineers have clear mind of developing technically, they have limited experience on environmental aspects and sustainability. The environmental managers may have some knowledge on LCA and life cycle perspective, but they rarely have in-depth technical knowledge. In order to overcome this barrier, a simplified LCA tool is needed for the technology developers to quickly review the design and improve it technically and environmentally by changing critical parameters such as efficiency, materials, and components.

For the BIPV applications in the real world, the Implementation Working Group on Photovoltaics (IWG PV)'s Strategic Energy Technology (SET) plan [65] has pointed out several challenges such as: (1) the availability of up-to-date georeferenced data of the building typology, building footprint and high resolution digital terrain model, (2) the missing of supporting tools and mechanisms for system integration such

Table 6
Summary of the eco-design guidelines.

Scale of application	Guideline	Recommended action	Benefit
Product	Consider the specific application of the BIPV modules to balance the benefits of electricity generation, weather protection and aesthetic value.	• Use silicon based BIPV module for application that does not require high transmittance. • Use frameless PV laminates and special mounting system for fully integrated BIPV roof installation. • Apply thin-film layer on rigid substrate for rooftop installation. • Use colour glass, perovskite materials and combinations of materials for applications which require high transmittance, such as glass houses' roofs and walls, façade and windows.	• Maximize the benefits of electricity generation while ensuring the requirements of weather protection and aesthetics of building envelop. • Fulfil the need of the customers.
Component	Focus on environmental and economic hotspots such as PV cell, EVA, mounting system and glass.	• Increase the energy efficiency of cell manufacturing for silicon-based PV cells. sourcing electricity for cell manufacturing from clean and renewable energy sources. • Improve the material efficiency and further study on new materials for EVA and mounting system. • Further study to reducing the cost of colour glass and improving the efficiency/ productivity of cell manufacturing for PSCs.	• Reduce the environmental impacts of the components. • Reduce the cost of the new cells and components.
Material	Further study innovative materials and combinations of materials for absorber layer, electron transport layer and glass	• Improving the efficiency and lifetime of perovskite materials by combining it with other materials. • Further study to combine materials for different layers of the cells.	• Maximize the PCE and transmittance simultaneously.
Life cycle	Recycle the BIPV modules when they reach their end of life	• Increase the efficiency of the recycling process. • Encourage the use of recovered and recycled materials and modules.	• Minimize the use of virgin materials. • Minimize the environmental impacts of modules for their whole life cycle.

as 'smart demand' response programs, smart contract based on the use of distributed metering of the energy flow and on the use of blockchain, sector coupling, improved ancillary service, distributed metering and sensors to improve the grid observability, electrical storage, electric vehicle and e-charging stations and (3) the need of a facility for the technological, aesthetical and energy integration of BIPV modules.

In order to develop BIPV modules sustainably, the IWG PV's SET plan recommended to define the key performance indicators in a life cycle perspective and in accordance with PEF, with the combined economic and environmental performance [65]. Therefore, the LCA and LCC studies on BIPV module, and a list of suggested eco-design measures (as this study) are needed. The application of these eco-design measures will reduce the environmental impacts of BIPV and optimize the cost of electricity and economic value of BIPV, consequently support the sustainability of BIPV.

As the volume of newly installed PV panels increases, there is also a concern on the increased volume of decommissioned PV panels and related waste, which is applicable for both solar PV and BIPV modules. Hence, the attention should be address to the resource depletion of minerals, metals and critical raw materials, the PV end-of-life management strategies such as recovery and recycling and circular supply chain with the use of secondary raw materials and material with low environmental impacts or less critical.

As a source of renewable energy, the exploitation of solar PV will contribute to the decarbonization of the economy, aiming at climate targets. The eco-design of BIPV will further reduce its life cycle GHG emissions, with double benefits in both energy and building sectors. Apart from GHG emissions, other critical impacts such as toxicity, raw material consumption are minimized, which supports the transition towards environmental sustainability. At the same time, the eco-design of innovative BIPV, e.g. perovskite based BIPV in this study, aims at the prevention of any potential environmental impacts at the early stage of development, so that the environmental impacts of the new technology can be reduced, while delivering the best technical performance, minimizing the production cost, bringing it close to the market. Consequently, it touches the economic sustainability and is relevant to at least five sustainable development goals (SDGs) on SDG7 affordable and clean energy, SDG9 industry, innovation and infrastructure, SDG11 sustainable city and communities, SDG12 sustainable production and consumption and SDG13 climate action.

3.6. Sensitivity analysis and uncertainty analysis

Sensitivity analysis is conducted to assess the robustness of the results to variations in key input parameters and assumptions. This can be done by conducting several scenarios, changing some critical parameters. In the existing attributional LCA in the energy sector, sensitivity analysis is frequently conducted by changing the electricity mix, or sources of energy/electricity consumed during the life cycle of the product system. Other study changed the weighting factors of indicators to see how they affect the results [66]. In consequential LCA which is relevant to the whole economy and covers several countries, the sensitivity analysis may be done by changing the number of economic sectors, countries or regions, as being studied in Ref. [67]. This study includes several sensitivity analyses, by quantifying the life cycle environmental impacts and costs of BIPV, with some alterations in critical parameters such as transmittance, PCE, components, materials and end-of-life management strategies.

As it is identified that PV cell is the largest contributor to most of the impact categories, a sensitivity analysis is conducted on electricity consumption for PSC manufacturing. Instead of being manufacturing in an Italian laboratory, the PSC is manufactured with EU grid mix and Chinese grid. In case of using the EU grid mix, most of the impact categories experience a small change, except for the case of EP-fw, IR, ODP. Specifically, the EP-fw triples and IR increases four times, while the ODP decreases by a third when the EU grid mix is used for fabricating the cells. In case of using the Chinese grid for fabricating the cells, most of the impacts increase significantly from two to ten times. Only ODP decrease two thirds, and IR and WU reduce slightly. The changes in the environmental impacts of PSC per cm^2 when different electricity sources are used for fabricating the cells, are illustrated in Fig. 7.

The uncertainty analysis is conducted for the life cycle environmental impacts per cm^2 of PSC, with Monte Carlo analysis integrated in the SimaPro software [68], aiming at evaluating the parameter uncertainty of the Ecoinvent background datasets and their impacts on the overall distribution of the obtained results. The results of uncertainty analysis are presented in Table 7. For most of the impact categories, the mean and median values are close to each other, indicating that the results are symmetric. Except for the cases of HT-nc and WU, with a large range between the mean and median values, which suggest the heavily skew of results, toward the negative value in case of HT-nc and toward the high value in case of WU. The standard deviation (SD) is relatively small compared to the means in some cases such as AP, GWP, HT-nc, RU-m, indicating the small variability in the obtained results. The coefficients of variance (CV) are high across all impact categories, indicating a relatively significant variation compared to the mean. For some impact categories such as ET-fw, IR, HT-c, HT-nc and WU, the CVs are extremely high, implying that some extreme values dominate the obtained results. Comparison of the percentiles at 2.5 % and 97.5 % indicates that half of the impact categories, including ET-fw, EP-fw, HT-c, HT-nc, IR, LU, ODP, PCOF and WU experience a wide range of values, especially for the case of ET-fw, HT-c and HT-nc and WU with negative value for 2.5 % percentile and positive value for 97.5 % percentile, suggesting the presence of many extreme value which lie far from the mean. The standard errors of the mean (SEM) are relatively small in most of the cases, indicating that the mean is a precise estimate of the population, though the high variabilities in mean vs median, and large spread between percentile 2.5 % and 97.5 % in some indicators such as ET, HT and WU make the mean less representative.

4. Conclusion

The paper reports the life cycle environmental impacts and LCOE of BIPV modules based on silicon and perovskite materials and proposed several eco-design guidelines and measures for technology's development. Regarding the environmental impacts, the GWP of BIPV modules ranges from 2.31E-02 $kgCO_2e$ to 6.83E-01 $kgCO_2e$, RU-f varies between 2.74E-01 MJ and 1.05E+01 MJ, and RU-m is from 1.63E-06 kg Sb eq to 1.14E-04 kg Sb eq per kWh. The large range of impacts is caused by the variety in the transmittance, materials of the solar cells and end-of-life management strategies. Besides, the LCOE generated from BIPV modules ranges from 0.01 EUR to 3 EUR per kWh, depending on the materials of solar glass and PV cells.

Considering that BIPV is solar PV which are mounted physically on the built envelop, the life cycle impacts and costs of BIPV modules are similar to the standard PV, especially for rooftop application. For window and façade installations, the aesthetics and transmittance requirements will affect the PCE of the module, consequently, cause an increase in environmental impacts, and also LCOE. Therefore, the eco-design of BIPV modules need to balance the transmittance and PCE for specific applications in order to achieve the most desired customers' demand. Besides, the eco-design of BIPV modules should focus some critical components such as PV cells, EVA, mounting system and colour glass, due to its large contribution to several environmental impacts and cost.

The comparison between silicon and perovskite based BIPV modules indicates that at the current stage of research and development, perovskite material cannot compete with silicon for BIPV applications in both environmental and economic aspects. In order to compete with conventional PV cells, innovative PV cells such as PSC need to improve its efficiency and increase its lifetime.

The paper develops a comparison of two materials for BIPV. While the SSC is a mature technology, the PSC is an emerging technology and now under laboratory study. At this early stage, there are potential for identifying the best technological design and optimize the technology environmentally and economically. However, there are difficulties in term of data collection. The data may be unavailable, incomplete, or in most of the cases, uncertain. The limitation of data for an emerging technology such as PSC, and the difference in the maturity of two technologies somehow cause an unfair comparison between the two materials. We recommended that the results of the study should be treated as oriented information to state which module is preferred to the other, not for quantitative comparisons of BIPV modules in absolute terms. The lack of data also points out the importance of scenario analysis to understand how different factors such as PCE, transmittance, lifetime, end-of-life management strategies and etc can affect the life cycle environmental impacts and cost of the BIPV module.

The paper applied the attributional LCA, which is a static model for

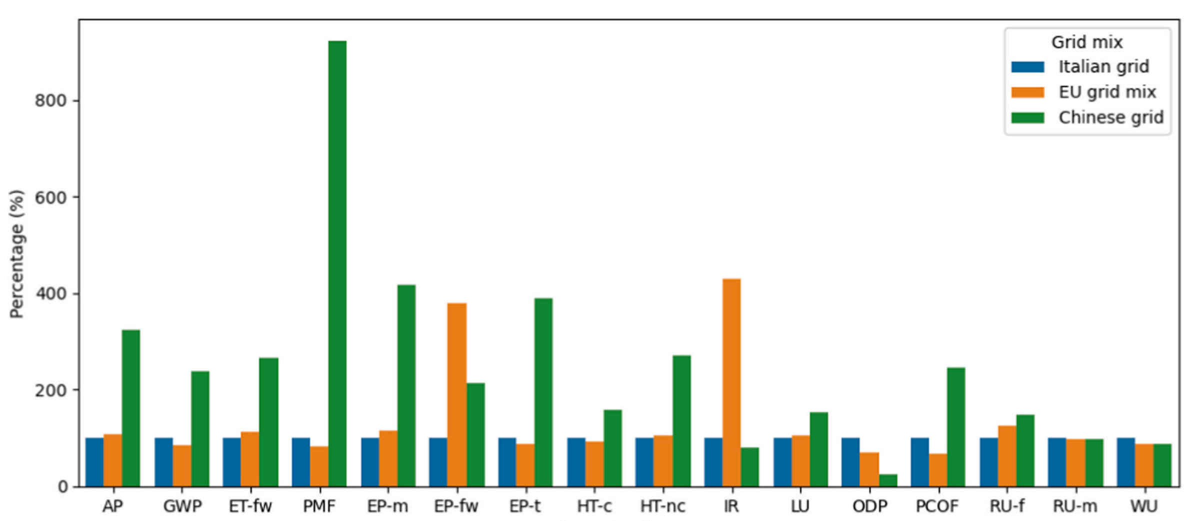

Fig. 7. Sensitivity analysis with different grid mixes for fabricating PSC. Notes: Acidification potential: AP, Global warming potential: GWP, Ecotoxicity – freshwater: ET-fw, Particulate matter formation: PMF, Eutrophication potential – marine: EP-m, Eutrophication potential – freshwater: EP-fw, Eutrophication potential-terrestrial: EP-t, Human toxicity – cancer: HT-c, Human toxicity – non cancer: HT-nc, Ionizing radiation: IR, Land use: LU, Ozone depletion potential: ODP, Photochemical ozone formation: PCOF, Resource use - fossil: RU-f, Resource use – mineral and metal: RU-m, Water use: WU.

Table 7
Uncertainty analysis of life cycle environmental impacts per cm^2 of PSC.

Impact	Unit	Mean	Median	SD	CV	2.50 %	97.50 %	SEM
AP	mol H+ eq	1.17E-03	1.17E-03	6.44E-05	5.49E+00	1.06E-03	1.31E-03	2.04E-06
GWP	kg CO_2 eq	3.00E-01	2.99E-01	2.06E-02	6.85E+00	2.63E-01	3.44E-01	6.51E-04
ET-fw	CTUe	7.37E-01	6.67E-01	2.56E+00	3.47E+02	−4.50E+00	5.85E+00	8.09E-02
EP-fw	kg P eq	6.85E-05	6.02E-05	3.50E-05	5.11E+01	3.22E-05	1.48E-04	1.11E-06
EP-m	kg N eq	1.93E-04	1.91E-04	2.04E-05	1.05E+01	1.59E-04	2.41E-04	6.44E-07
EP-t	mol N eq	2.20E-03	2.18E-03	2.28E-04	1.04E+01	1.82E-03	2.74E-03	7.22E-06
HT-c	CTUh	9.80E-11	8.98E-11	9.50E-10	9.70E+02	−1.82E-09	1.96E-09	3.00E-11
HT-nc	CTUh	2.34E-09	−7.31E-09	1.94E-07	8.31E+03	−3.89E-07	3.89E-07	6.14E-09
IR	kBq U-235 eq	3.80E-02	2.55E-02	4.12E-02	1.08E+02	1.13E-02	1.38E-01	1.30E-03
LU	Pt	8.79E-01	8.69E-01	1.21E-01	1.37E+01	6.57E-01	1.14E+00	3.81E-03
ODP	kg CFC11 eq	6.98E-09	6.66E-09	1.64E-09	2.35E+01	4.74E-09	1.08E-08	5.19E-11
PMF	disease inc.	5.72E-09	5.62E-09	6.49E-10	1.14E+01	4.78E-09	7.35E-09	2.05E-11
PCOF	kg NMVOC eq	9.18E-04	8.97E-04	1.46E-04	1.59E+01	6.87E-04	1.27E-03	4.61E-06
RU-f	MJ	4.63E+00	4.54E+00	7.56E-01	1.63E+01	3.37E+00	6.40E+00	2.39E-02
RU-m	kg Sb eq	5.14E-05	5.13E-05	2.01E-06	3.91E+00	4.77E-05	5.58E-05	6.36E-08
WU	m^3 depriv.	1.07E+00	5.02E+00	3.82E+01	3.56E+03	−8.06E+01	6.75E+01	1.21E+00

Notes: Standard deviation: SD, Coefficient of variance: CV, Standard error of the mean: SEM, Acidification potential: AP, Global warming potential: GWP, Ecotoxicity – freshwater: ET-fw, Particulate matter formation: PMF, Eutrophication potential – marine: EP-m, Eutrophication potential – freshwater: EP-fw, Eutrophication potential-terrestrial: EP-t, Human toxicity – cancer: HT-c, Human toxicity – non cancer: HT-nc, Ionizing radiation: IR, Land use: LU, Ozone depletion potential: ODP, Photochemical ozone formation: PCOF, Resource use - fossil: RU-f, Resource use – mineral and metal: RU-m, Water use: WU.

quantifying the potential environmental impacts of product and service. The model is suitable for studying the stand-alone solar PV and BIPV module. It is also perfect for this case study as the development of emerging PSC and innovative BIPV modules are at the initial stage. In case the module is integrated into the building, the model should be more robust, to include the instant change of energy production and consumption by hours, days, or seasons. The suggested model for this case is dynamic LCA. Besides, considering the diffusion of BIPV in the future, the application of consequential LCA is recommended to take into account the rebound and spill-over effect of BIPV application at large scale.

It is recommended that the recycling of the emerging PV cells such as PSC should be further studied. The current recycling strategies which perform well in recovering the metals, plastic and glass, could be extended to recover perovskite materials to minimize the environmental impacts and cost of electricity generated by the perovskite based BIPV modules. All of these measures will support the development of BIPV modules which is not only response to the decarbonization of energy and building sectors, but also the potential answer for coping with material shortage and supporting the circular economy.

BIPV has a huge potential for further development and application; however, in the case of Italian BIPV sector, the current mechanism does not take into account the speciality of BIPV, the target for BIPV is missing, and the exiting measures such as self-consumption, tax deduction, net billing, energy income are the same for BIPV and solar PV [65]. Therefore, a comprehensive development of mechanism and frameworks for supporting BIPV should be further studied to support the large deployment of BIPV.

Besides, module and installation costs are another barrier. While the cost for standardized BIPV product is similar to that of solar PV, the customized BIPV products with colour glass, transparent glass, BIPV tiles, and tiles with water-proof mounting system are more expensive. The high cost mostly originates from new technologies (in the case of colour glass and transparent glass) and cost for certification and permit [65] (for installing of BIPV on traditional tiles, or BIPV tiles on historical buildings or heritages). It is recommended that on one hand, the incentives are needed for particular BIPV product that meet the request of cultural authorities, and on the other hand further studies to optimize the cost of BIPV module should be encouraged.

Nomenclature

a-Si	Amorphous silicon

(*continued on next column*)

(*continued*)

AP	Acidification
BICPV	Building integrated concentrated photovoltaics
BIPV	Building integrated photovoltaics
BIPV/T	Building integrated photovoltaics/thermal
c-Si	Crystalline silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
cm^2	Square centimeter
CSP	Concentrating solar power
CST	Concentrating solar thermal
CV	Coefficient of variance
EP-fw	Eutrophication, freshwater
EP-m	Eutrophication, marine
EP-t	Eutrophication, terrestrial
EPS	Environmental Priority Strategies
ET-fw	Ecotoxicity, freshwater
EVA	Ethylene-vinyl acetate
g	Gram
GHG	Greenhouse gas
GWP	Global warming potential
HT-c	Human toxicity, cancer
HT-nc	Human toxicity, non-cancer
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IR	Ionizing radiation
IWG PV	Implementation Working Group on Photovoltaics
kg	Kilogram
kWh	Kilowatt hour
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCOE	Levelized cost of electricity
LU	Land use
m^2	Square meter
mc-Si	Multi-crystalline silicon
NEST	Network for Sustainable Energy Transition
ODP	Ozone depletion
PCE	Power conversion efficiency
PCM	Phase change material
PCOF	Photochemical ozone formation
PEF	Product environmental footprint
PMF	Particulate matter
PSC	Perovskite solar cell
PTAA	Poly(triarylamine)
PV	Photovoltaics
PV/T	Photovoltaics/thermal
RU-f	Resource use, fossils
RU-m	Resource use, minerals and metals
sc-Si	Single-crystalline silicon

(*continued on next page*)

(*continued*)

SD	Standard deviation
SDG	Sustainable development goal
SEM	Standard error of the mean
SET	Strategic Energy Technology
SSC	Silicon solar cell
tkm	Tonne kilometer
WEEE	Waste from electrical and electronic equipment
Wp	Watt peak
WU	Water use

CRediT authorship contribution statement

Le Quyen Luu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Maurizio Cellura:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Francesco Guarino:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Sonia Longo:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Le Quyen Luu, Maurizio Cellura and Francesco Guarino reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] EEA. In: Total GHG emissions and removals in the EU; 2024. https://doi.org/10.2909/6331f651-8863-4656-a911-669f2a332a1e.
[2] EEA. Greenhouse gas emissions from energy use in buildings in Europe. 2024.
[3] IEA. Net zero by 2050 A roadmap for the global energy sector. International Energy Agency; 2021.
[4] Kazaz O, Karimi N, Paul MC. Optically functional bio-based phase change material nanocapsules for highly efficient conversion of sunlight to heat and thermal storage. Energy 2024;305:132290. https://doi.org/10.1016/j.energy.2024.132290.
[5] Naghipour P, Naghipour A. Energy performance analysis of residential buildings in Bandar Anzali: influence of orientation and aspect ratio. Sustain 2025;5:100140. https://doi.org/10.1016/j.nxsust.2025.100140.
[6] Healey Trulsrud T, Van Der Leer J. Towards a positive energy balance: a comparative analysis of the planning and design of four positive energy districts and neighbourhoods in Norway and Sweden. Energy Build 2024;318:114429. https://doi.org/10.1016/j.enbuild.2024.114429.
[7] Bosu I, Mahmoud H, Ookawara S, Hassan H. Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: a comprehensive review. Sol Energy 2023;259:188–228. https://doi.org/10.1016/j.solener.2023.05.006.
[8] Kanters J, Wall M. Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden. Urban Plan Transp Res 2018;6:54–80. https://doi.org/10.1080/21650020.2018.1478323.
[9] Zhang J, Gao X, Deng Y, Li B, Yuan C. Life cycle assessment of titania perovskite solar cell technology for sustainable design and manufacturing. ChemSusChem 2015;8:3882–91. https://doi.org/10.1002/cssc.201500848.
[10] IEA. The role of critical minerals in clean energy transitions. 2022.
[11] Montana F, Cellura M, Di Silvestre ML, Longo S, Luu LQ, Riva Sanseverino E, Sciumè G. Assessing critical raw materials and their supply risk in energy technologies—A literature review. Energies 2024;18:86. https://doi.org/10.3390/en18010086.
[12] Zhang X, Shen J, Lu Y, He W, Xu P, Zhao X, Qiu Z, Zhu Z, Zhou J, Dong X. Active solar thermal facades (ASTFs): from concept, application to research questions. Renew Sustain Energy Rev 2015;50:32–63. https://doi.org/10.1016/j.rser.2015.04.108.
[13] Binda T, Bottero M, Bisello A. Evaluating positive energy districts: a literature review. In: Calabrò F, Della Spina L, Piñeira Mantiñán MJ, editors. New metropolitan perspectives, lecture notes in networks and systems. Cham: Springer International Publishing; 2022. p. 1762–70. https://doi.org/10.1007/978-3-031-06825-6_170.
[14] Volpe R, Bisello A, Tuerk A, Guarino F, Giancola E, Sanchez MN, Tumminia G, Marrasso E, Pallotta G, Cutore E, Cellura M, Fichera A, Longo S, Roselli C, Sasso M, Zhang X, Marotta I, Brunetti A, Rincione R, Reda F. Linking environmental impact assessment and positive energy districts: a literature review. Clean Environ Syst 2025;16:100264. https://doi.org/10.1016/j.cesys.2025.100264.
[15] Abdelrazik AS, Shboul B, Elwardany M, Zohny RN, Osama A. The recent advancements in the building integrated photovoltaic/thermal (BIPV/T) systems: an updated review. Renew Sustain Energy Rev 2022;170:112988. https://doi.org/10.1016/j.rser.2022.112988.
[16] Brahim T, Jemni A. Economical assessment and applications of photovoltaic/thermal hybrid solar technology: a review. Sol Energy 2017;153:540–61. https://doi.org/10.1016/j.solener.2017.05.081.
[17] Jing Y, Zhu L, Yin B, Li F. Evaluating the PV system expansion potential of existing integrated energy parks: a case study in North China. Appl Energy 2023;330:120310. https://doi.org/10.1016/j.apenergy.2022.120310.
[18] Krarti M. Evaluation of energy performance for rotating residential buildings integrated with rooftop PV systems. Appl Energy 2025;383:125407. https://doi.org/10.1016/j.apenergy.2025.125407.
[19] Lim JW, Kim H. Predicting the energy, economic, and environmental performance of next-generation photovoltaic technologies in residential buildings. Appl Energy 2025;390:125895. https://doi.org/10.1016/j.apenergy.2025.125895.
[20] Yang X, Wang Y, Wang R, Zhang H, Chen H, Huang J, Gao D. Integrated PV/T coupled PEM system for low-carbon office buildings: dynamic simulation, multi-energy synergy, and economic analysis. Energy 2025;330:136945. https://doi.org/10.1016/j.energy.2025.136945.
[21] Lai Y-Y, Yang S, Fan L-W. Analysis and optimization of the performance of a solar PV/T system integrated with seasonal latent heat storage for decarbonized heating and hot water supply. Energy 2025;331:137069. https://doi.org/10.1016/j.energy.2025.137069.
[22] Bird M, Andraos R, Acha S, Shah N. Lifetime financial analysis of a model predictive control retrofit for integrated PV-battery systems in commercial buildings. Energy Build 2025;332:115459. https://doi.org/10.1016/j.enbuild.2025.115459.
[23] Tang H, Li B, Zhang Y, Pan J, Wang S. A coordinated predictive scheduling and real-time adaptive control for integrated building energy systems with hybrid storage and rooftop PV. Renew Energy 2025;239:122047. https://doi.org/10.1016/j.renene.2024.122047.
[24] Kamthania D, Tiwari GN. Energy metrics analysis of semi-transparent hybrid PVT double pass facade considering various silicon and non-silicon based PV module hyphen is accepted. Sol Energy 2014;100:124–40. https://doi.org/10.1016/j.solener.2013.11.015.
[25] Ritzen MJ, Houben JJM, Rovers R, Vroon ZAEP, Geurts CPW. Carrying capacity based environmental impact assessment of building integrated photovoltaics. Sustain Energy Technol Assessments 2019;31:212–20. https://doi.org/10.1016/j.seta.2018.12.006.
[26] Rossi F, Jelagat Kipyator M, Aernouts T, Pettersson H, Basosi R, Parisi ML, Sinicropi A. Unveiling the potential of perovskite solar systems in building integrated installations: a consequential and prospective life cycle assessment and economic analysis. Energy Build 2024;312:114214. https://doi.org/10.1016/j.enbuild.2024.114214.
[27] Jayathissa P, Jansen M, Heeren N, Nagy Z, Schlueter A. Life cycle assessment of dynamic building integrated photovoltaics. Sol Energy Mater Sol Cells 2016;156:75–82. https://doi.org/10.1016/j.solmat.2016.04.017.
[28] Crawford RH, Treloar GJ, Fuller RJ, Bazilian M. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renew Sustain Energy Rev 2006;10:559–75. https://doi.org/10.1016/j.rser.2004.11.005.
[29] Chow T-T, Ji J. Environmental life-cycle analysis of hybrid solar photovoltaic/thermal systems for use in Hong Kong. Int J Photoenergy 2012;2012:1–9. https://doi.org/10.1155/2012/101968.
[30] Royo P, Ferreira VJ, López-Sabirón AM, Ferreira G. Hybrid diagnosis to characterise the energy and environmental enhancement of photovoltaic modules

using smart materials. Energy 2016;101:174–89. https://doi.org/10.1016/j.energy.2016.01.101.
[31] Li Q, Monticelli C, Kutlu A, Zanelli A. Feasibility of textile envelope integrated flexible photovoltaic in Europe: carbon footprint assessment and life cycle cost analysis. J Clean Prod 2023;430:139716. https://doi.org/10.1016/j.jclepro.2023.139716.
[32] Li Z, Zhang W, Xie L, Wang W, Tian H, Chen M, Li J. Life cycle assessment of semi-transparent photovoltaic window applied on building. J Clean Prod 2021;295:126403. https://doi.org/10.1016/j.jclepro.2021.126403.
[33] Menoufi K, Chemisana D, Rosell JI. Life cycle assessment of a building integrated concentrated photovoltaic scheme. Appl Energy 2013;111:505–14. https://doi.org/10.1016/j.apenergy.2013.05.037.
[34] Parascanu MM, Keiner D, Breyer C, Macé P, Lizasoain-Arteaga E. Comprehensive prospective environmental assessment of innovative photovoltaic technologies: integration into electricity grids in Finland, Germany, and Spain. Energy 2025;315:134454. https://doi.org/10.1016/j.energy.2025.134454.
[35] Battisti R, Corrado A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy 2005;30:952–67. https://doi.org/10.1016/j.energy.2004.07.011.
[36] Lamnatou Chr, Baig H, Chemisana D, Mallick TK. Dielectric-based 3D building-integrated concentrating photovoltaic modules: an environmental life-cycle assessment. Energy Build 2017;138:514–25. https://doi.org/10.1016/j.enbuild.2016.12.038.
[37] Sierra D, Aristizábal AJ, Hernández JA, Ospina D. Life cycle analysis of a building integrated photovoltaic system operating in Bogotá, Colombia. Energy Rep 2020;6:10–9. https://doi.org/10.1016/j.egyr.2019.10.012.
[38] Fares H, Lobaccaro G, Gazbour N, Rasmussen FN, Chèze D, Le Pierrès N, Wurtz E. A methodology for assessing environmental impact of building integrated PV in low carbon footprint electricity generation context. Energy Build 2025;329:115219. https://doi.org/10.1016/j.enbuild.2024.115219.
[39] ISO. ISO 14040: environmental management -Life cycle assessment - principles and framework. 1997.
[40] Horne R. Life cycle assessment: origins, principles and context. In: Life cycle assessment - principles, practice and prospects. Collingwood: CSIRO Publishing; 2009. p. 1–8.
[41] Luu LQ, Longo S, Cellura M, Sanseverino ER. A review on consequential life cycle assessment in the power sector. Int J Sustain Dev Plann 2020;15:1157–68. https://doi.org/10.18280/ijsdp.150802.
[42] ISO. Environmental management - life cycle assessment – principles and framework, ISO 14040:2006. Geneva: International Organization for Standardization; 2006.
[43] ISO. Environmental management - life cycle assessment – requirements and guidelines, ISO 14044:2006. Geneva: International Organization for Standardization; 2006.
[44] Frischknecht R, Heath G, Raugei M, Sinha P, de Wild-Scholten M. Methodology guidelines on life cycle assessment of photovoltaic electricity (no. IEA-PVPS T12-08:2016). International Energy Agency; 2016.
[45] Frischknecht R, Stolz P, Heath G, Raugei M, Sinha P, Wild-Scholten De. Methodology guidelines on life cycle assessment of photovoltaic 2020. 2020.
[46] EC. Understanding product environmental footprint and organisation environmental footprint methods [WWW Document]. URL, https://circabc.europa.eu/ui/group/6e9b7f79-da96-4a53-956f-e8f62c9d7fed/library/537534a4-9c76-40a1-b488-e9127db2befd/details?download=true; 2021.
[47] Lichtenvort K, Rebitzer G, Huppes G, Ciroth A, Seuring S, Schmidt WP, Gunther E, Hoppe H, Swarr T, Hunkeler D. History of life cycle costing, its categorization and its basic framework. In: Hunkeler D, Lichtenvort K, Rebitzer G, editors. Environmental life cycle costing. New York: CRC Press and SETAC Press; 2008.
[48] Energy Matching, n.d. Italian demo site.
[49] European Parliament. Directive 2012/19/EU of the european parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE). 2012.
[50] Frischknecht R, Itten R, Sinha P, De Wild-Scholten M, Zhang J, Heath GA, Olson C. Life cycle inventories and life cycle assessments of photovoltaic systems. No. NREL/TP-6A20-73853, 1561526, https://doi.org/10.2172/1561526; 2020.
[51] IEA. Advances in photovoltaic module recycling literature review and update to empirical life cycle inventory data and patent review. 2024.
[52] IEA. Life cycle inventory of current photovoltaic module recycling processes in Europe. 2017.
[53] Ecoinvent, n.d. Ecoinvent database version 3.7 [WWW Document]. URL https://ecoinvent.org/the-ecoinvent-database/.
[54] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017;22:138–47. https://doi.org/10.1007/s11367-016-1246-y.
[55] Khan AA, Molina P, Reichel C, Protti AA, Neuhaus DH, Rentsch J, Nold S. The European Union's ecodesign directive – analysis of carbon footprint assessment methodology and implications for photovoltaic module manufacturers. Sol RRL 2024;8:2301011. https://doi.org/10.1002/solr.202301011.
[56] Luu LQ, Cellura M, Longo S, Guarino F. A comparison of the life-cycle impacts of the concentrating solar power with the product environmental footprint and ReCiPe methods. Energies 2024;17:4461. https://doi.org/10.3390/en17174461.
[57] Virtuani A, Borja Block A, Wyrsch N, Ballif C. The carbon intensity of integrated photovoltaics. Joule 2023;7:2511–36. https://doi.org/10.1016/j.joule.2023.09.010.
[58] European Commission, n.d. Waste from electrical and electronic equipment.
[59] Philipps DS, Ise F, Warmuth W, GmbH PP. Photovoltaics report. 2023.
[60] Gholami H, Nils Røstvik H, Manoj Kumar N, Chopra SS. Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: solsmaragden case study in Norway. Sol Energy 2020;211:488–502. https://doi.org/10.1016/j.solener.2020.09.087.
[61] IEA. Building integrated photovoltaic policies in Italy. 2021.
[62] Nonni E, Matteocci F, Serenelli L, Castriotta LA, Barichello J, Magliano E, Di Girolamo D, Martini L, Menchini F, Izzi M, Di Carlo A, Tucci M. A holistic approach for a large area (>1 cm2) mechanically stacked two terminal tandem perovskite/silicon heterojunction with efficiencies above 30 %. Sol Energy Mater Sol Cells 2025;292:113740. https://doi.org/10.1016/j.solmat.2025.113740.
[63] Barichello J, Paci B, Moras P, Hajhemati J, Generosi A, Riva FR, Cacovich S, Jafarzadeh F, Brunetti F, Carlo AD, Matteocci F. Exploiting the impact of ionic liquids and light exposure on performance of fully inorganic CsPbBr3 semi-transparent perovskite solar cells. Sol Energy 2025;287:113237. https://doi.org/10.1016/j.solener.2024.113237.
[64] Ghosh S, Emeka OC, Cho S, Di Carlo A, Kim J. Advancements in see-through solar technology employing ITO/Ag/ITO spectral beam splitter. Opt Mater 2025;166:117191. https://doi.org/10.1016/j.optmat.2025.117191.
[65] IWG PV. A strategic plan for research and innovation to relaunch the Italian photovoltaic sector and contribute to the targets of the national energy and climate plan. 2020.
[66] Ardente F, Beccali G, Cellura M. Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS.". Ecol Model 2003;163:101–18.
[67] Luu LQ, Cellura M, Nguyen TQ, Nguyen HN, Nguyen QN. The aggregation issue in quantifying sectorial and national GHG emissions using H-MRIO models. In: 2023 Asia meeting on environment and electrical engineering (EEE-AM). Presented at the 2023 Asia meeting on environment and electrical engineering (EEE-AM). Hanoi, Vietnam: IEEE; 2023. p. 1–7. https://doi.org/10.1109/EEE-AM58328.2023.10395611.
[68] Sustainability PRé. SimaPro. 2021.