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Photovoltaics for buildings and greenhouses: Organic solar cells and other technologies

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ABSTRACT

In light of the increasing environmental awareness, the present study is about life-cycle assessment of the Balance of System (BOS) of Photovoltaics (PVs), underlining the advantages of Organic Photovoltaics (OPVs). A closer look at the literature on PV shows that there is a dearth of studies which place emphasis on PVs with lightweight BOS systems, highlighting the importance of flexible/lightweight PV modules for buildings and greenhouses. To fill this literature gap, the present article sets out to: i) offer an overview of BOS, ii) analyse the environmental profile of the BOS of a grid-connected PV rooftop system, iii) estimate the avoided impacts of PV systems which need small amounts of BOS materials and iv) present critical factors for OPV greenhouses and PV challenges. Considering the results of the present study as well as results of other studies, BOS impacts range from: i) 6 to 181 kg $CO_{2.eq}/m^2$ of PV module, ii) 55 to 1900 MJ_{prim}/m^2 of PV module. On the other hand, taking into account that the avoided impacts of a PV system are inextricably linked to the electricity mix of a certain country, a case study based on different electricity mixes (OPV system: Spain; Italy; Portugal) is presented.

Introduction

It is known that solar systems play a pivotal role in mitigating climate change, offering different kinds of systems/applications such as solar thermal, Photovoltaic (PV) and hybrid Photovoltaic/Thermal (PVT), for buildings, industry [1], greenhouses [2], cooling/heating systems for remote areas [3], etc.

Solar systems can be classified based on different criteria: Building-Added (BA) (for example: BA PV; BA PVT) [4] vs Building-Integrated (BI) (for instance: BIPV; BIPVT) [5]; small-scale [1] vs large-scale applications (namely PV power plants [6]); non-concentrating vs concentrating systems (e.g. Concentrating PV (CPV) and Concentrating PVT (CPVT) [4]). The systems mentioned above consist of PV (or PVT) modules and additional components such as ground-mounting structures, inverters, cabling, transformers and connectors. These supplementary elements are known as Balance of System (BOS) [7].

Taking into account that environmental Life Cycle Assessment (LCA) is a useful tool, in the literature on PV/PVT there are numerous LCA studies. Perez et al. [8] presented an LCA of a BIPV system with mono-Si PV cells, in New York City. Energy Payback Time (EPBT), Energy Return on Investment (EROI), Global Warming Potential (GWP) and other environmental indicators were examined. Serrano-Luján et al. [9] conducted an LCA of different types of PV technologies. With regard to PVT LCA, Tripanagnostopoulos et al. [4,10] found that PVT configurations show better environmental profiles in comparison to standard PV panels.

The literature review of PV/PVT shows that some LCA studies placed emphasis on the modules, without involving BOS. However, BOS materials are critical [11]. Baharwani et al. [12] noted that the environmental performance of a PV system depends on factors such as solar irradiance, lifespan, BOS components, PV cells and material-manufacturing processes.

Although BOS materials can have a considerable influence on the environmental profile of a PV system [13], there are PV LCA studies that do not consider BOS impact and place emphasis on the impacts related to the PV modules [14]. Espinosa et al. [15] mentioned that little attention has been paid to PV LCA studies which take into account BOS and inventory data for BOS components are scarce. Jungbluth et al. [16] noted that, in certain cases, BOS elements are responsible for 30–50% of the whole PV-system impact.

Regarding PV systems with solar concentration, especially in the case of large-scale applications, additional components such as trackers and support structures remarkably influence the environmental impact of the whole system [17].

To sum up, the literature review of traditional PV systems shows that

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Nomenclature

ALCPC	Air-gap-lens-walled compound parabolic concentrator
BA	Building-Added
BA PV	Building-Added Photovoltaic
BA PVT	Building-Added Photovoltaic/Thermal
BI	Building-Integrated
BIPV	Building-Integrated Photovoltaic
BIPVT	Building-Integrated Photovoltaic/Thermal
BOS	Balance of System
CED	Cumulative Energy Demand
CIGS	Copper indium gallium diselenide
CML	CML method
CO_2 PBT	Payback time based on CO_2 emissions
$CO_{2.eq}$	$CO_{2.equivalent}$
CPV	Concentrating Photovoltaic
CPVT	Concentrating Photovoltaic/Thermal
CTU_e	Comparative Toxic Unit for ecosystems
CTU_h	Comparative Toxic Unit for humans
DALY	Disability-Adjusted Life-Year
EC	Embodied Carbon
Eco-indicator 99	Eco-indicator 99 method
EE	Embodied Energy
EPBT	Energy Payback Time
EROI	Energy Return on Investment
GHG	Greenhouse Gas
GHG PBT	Greenhouse-Gas Payback Time
GJ_{prim}	GJ primary
GWP 100a	Global warming potential based on a time horizon of 100 years
GWP	Global Warming Potential
IPCC 2013 GWP 100a	IPCC 2013 GWP 100a method
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ_{prim}	MJ primary
NIR	Near-infrared radiation
OPV	Organic Photovoltaic
Pts	Points
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVT	Photovoltaic/Thermal
ReCiPe	ReCiPe method
(species.yr)	Loss of species over a certain area (during a certain time)
TRACI	TRACI method
USEtox	USEtox method

there is dearth of LCA studies which present a comprehensive environmental profile of BOS, based on multiple environmental indicators and different types of Life Cycle Impact Assessment (LCIA) methods. There are some studies which assessed BOS but, in most cases, they focused on GWP and primary energy demand.

On the other hand, in an effort to overcome some of the limitations associated with traditional PV systems (heavy PV panels, environmental impacts due to the BOS, etc.), in recent years there has been an increasing interest in Organic Photovoltaic (OPV) cells. OPVs are useful in numerous and diverse application domains, offerings lightweight, semi-transparent and flexible PV modules [15,18], OPV/ethylene tetrafluoroethylene modules for BI applications [19], OPV panels for greenhouses [20], etc. Regarding agricultural applications, during the last two years, there has been a growing interest in OPV greenhouses. Several studies were presented [20–28] but most of these studies focused on specific systems and did not present a general overview of OPV greenhouses. Overall, the results of OPV greenhouses are promising. It is, therefore, necessary to further investigate these burgeoning technologies, identifying critical factors for future greenhouses and agrivoltaics.

In light of the issues mentioned above, the present article sets out to present:

- A review of BOS materials/components.
- An environmental LCA of a BOS appropriate for traditional PVs for buildings, based on different LCIA methods and environmental indicators.
- Scenarios involving recycling.
- Avoided environmental impacts due to the use of PV systems that need a few kilogrammes of BOS materials (OPV systems).
- Critical factors for OPV greenhouses and challenges related to PV technologies.

The innovation of the present article is related to the fact that:

- It presents an overview of BOS components for different kinds of PV technologies/systems.
- It evaluates the environmental performance of a BOS appropriate for traditional PVs for buildings, assessing a whole host of environmental indicators related to Embodied Energy (EE), Embodied Carbon (EC), human health, ecosystems and so on.
- It analyses the avoided environmental impacts (based on different types of environmental indicators and LCIA methods) of a PV system (OPV technology) that uses small amounts of BOS materials. The analysis has been based on different electricity mixes: Spain; Italy; Portugal.
- It offers an overview of key factors for effective/efficient OPV greenhouses.

To sum up, the present study aims at:

1) Presenting information about BOS components which considerably influence the environmental performance of a traditional PV installation.
2) Underlining the importance of new PV technologies (for example flexible and lightweight OPV modules) to buildings and greenhouses.

The structure of the article is as follows:

- Part 1 (several kinds of PV technologies): Literature review and information about BOS/additional components for different types of PV systems.
- Part 2 (traditional PV technologies): LCA → the environmental profile of the BOS components of a conventional PV system for buildings.
- Part 3 (new PV technologies): Avoided environmental impacts → a case study of OPVs.
- Part 4 (new PV technologies): OPV greenhouses → key factors for efficient OPV greenhouses.
- Part 5 (traditional and new PV technologies): Challenges and future prospects.
- Part 6: Limitations of the present study and future research.

BOS – additional components for PV and PVT Systems: Literature review

Section "BOS – additional components for PV and PVT Systems: Literature review" presents an overview of BOS/additional components for different kinds of PV technologies, placing emphasis on traditional/conventional PV systems which require considerable amounts of materials.

Si-based PV systems without involving solar concentration - Emphasis: Buildings

Si-based PVs are widely used [29,30]. Fthenakis et al. [7] noted that in the case of rooftop PV applications, the BOS usually involves cables, inverters, support structures and connectors. Large-scale ground-mounted PV systems need additional components (for instance, office buildings and concrete). Information about the Life Cycle Inventory (LCI) was presented.

Raugei et al. [31] presented an inventory of typical grid-connected PV rooftop installations, highlighting the fact that lighter and/or BI support structures can appreciably reduce BOS impacts. Raugei et al. [31] proposed an inventory with many kilogrammes of steel:

- Frame (aluminium) 1.9 kg/m^2 of PV module
- Support structure (steel) 25 kg/m^2 of PV module
- Cables and contact boxes (copper) 0.04 kg/m^2 of PV module
- Cables and contact boxes (plastics) 0.04 kg/m^2 of PV module

An alternative option could be a BOS which has aluminium as the basic material [32].

In Table 1, selected studies which presented environmental issues about BOS for Si-based (non-concentrating) PV systems are presented. Emphasis has been placed on building applications. From Table 1, it can be seen that:

- Most of the studies examined primary energy demand and CO_2 emissions.
- Some investigations examined scenarios with/without involving BOS.
- There are studies which placed emphasis on material-manufacturing phase whereas other investigations took into account the full life-cycle of a system.
- Frames present high environmental impacts and, for this reason, scenarios which involve metal recycling are interesting.
- Energy consumption and CO_2 emissions vary, depending on factors such as the electricity mix of a country and fabrication processes.
- BOS electrical components (inverters, cables and so on) have low environmental impacts (in comparison to the mechanical ones and PV frames).
- By using sun tracking there is an additional impact but it is counterbalanced on the grounds that solar trackers enhance PV-cell efficiency.
- BIPV configurations do not require components such as ground mounting and frames and replace certain building elements (roofs, façades and so on).

Table 1
Studies which present/discuss BOS environmental profile: Si-based PV systems without involving solar concentration. Emphasis: buildings.

Study	System	Location	Materials and components (placing emphasis on BOS)	Environmental issues, methods, indicators	Findings
Keoleian and Lewis [33]	Amorphous-Si PV module	USA	With/without BOS	Energy analysis, EPBT, etc.	The aluminium frames of the modules have considerable energy inputs
Frankl et al. [29]	PV systems for buildings	Italy	BOS materials: Steel, primary and secondary aluminium, concrete, copper, glass, PVC, clay, etc.	Energy consumption, EPBT, CO_2 emissions, etc.	In most cases, the energy content of the BOS for PVs for buildings was approximately-three times lower in comparison to that of PV power plants
Battisti and Corrado (2005) [34]	A poly-Si PV system for BA (rooftop) on-grid applications	Italy	They focused on the mechanical parts of the BOS (e.g. mounting structures)	Cumulative Energy Demand (CED), $CO_{2.eq}$ emissions, EPBT, $CO_{2.eq}$ PBT, etc.	The mechanical elements of the BOS were responsible for 6% of the total primary energy demand
Alsema and de Wild-Scholten [35]	Si-based PV modules	Europe	BOS components: Array support, cabling, inverter	Primary energy demand, EPBT, CO_2 emissions, etc.	BOS impact [35,36]: array support and cabling → 100 MJ_{prim}/m^2 and 6.1 kg $CO_{2.eq}/m^2$; inverter → 1930 MJ_{prim}/kW_p and 125 kg $CO_{2.eq}/kW_p$
Kannan et al. [37]	A 2.7-kW_p PV system (36 mono-Si modules); rooftop	Singapore	BOS: Aluminium support structures, concrete blocks, inverters	Greenhouse-gas (GHG) emissions, EPBT, life-cycle primary energy use, etc.	Aluminium support structure was responsible for around 10% of the life-cycle energy inputs
Pacca et al. [38]	A 33-kW PV system on the roof of a building: poly-Si and thin-film (amorphous) PV modules	USA	Three combiner boxes, one 30-kW inverter and other BOS components	CO_2 emissions; EPBT, net energy ratio, etc.	Life-cycle impact of the BOS: 242 MJ/m^2 and 16.8 kg $CO_{2.eq}/m^2$; BOS EPBTs: 0.7–0.9 years, depending on the number of the inverters
Perpiñan et al. [39]	On-grid PV systems with/without tracking for buildings (mono-Si PV modules)	Longitude between: -10° and 10°; 30° and 45°	BOS: Trackers, inverters, support structures, wiring, etc.	EPBT, EE, etc.	Required energy: 39840 MJ for an average PV panel manufactured by Isofoton; EE: 1124.33 MJ/kW for an average inverter
Lu and Yang [40]	A grid-connected BIPV system (22 kW_p; mono-Si; rooftop)	Hong Kong	Mechanical and electrical components of the BOS, etc.	EPBT, GHG PBT, EE, etc.	EE: 71% of the total impact is because of the PV panels; BOS components are responsible for 29% of the total impact
Sumper et al. [41]	A 200-kW rooftop poly-Si PV system	Spain	BOS: Mounting structure, junction box, wires, inverter, etc.	CO_2 emissions, primary energy demand, EPBT, etc.	BOS: 6727.2 kg CO_2 emissions
Zhong et al. [42]	A poly-Si PV panel	Europe	BOS: Inverter, cables, frames	Eco-indicator 99	Landfill disposal scenario: the BOS does not have a remarkable contribution to the environmental impacts
Mohr et al. [30]	A roof-integrated flexible solar cell laminate with tandem cells (amorphous Si/nanocrystalline Si)	The Netherlands	BOS: connection box, cables, etc.	ReCiPe, CED, EPBT, etc.	The BOS (without the construction for roof integration) is responsible for 16% of the total primary energy demand

- PV systems (involving BOS) show EPBT values which are considerably lower than the lifespan of a typical PV system (around 25–30 years).
- Different climatic conditions/locations were examined.

An additional factor is BOS efficiency. Battisti and Corrado [34] considered a BOS efficiency of 80%. Frankl et al. [29] took into account a BOS electric efficiency of 85%.

Si-based PV systems without involving solar concentration - Emphasis: Power plants

In Table 2 investigations about Si-based PV plants (non-concentrating), are presented. It can be noted that:

- In the future, further reduction in the impacts of large-scale PV applications will occur.
- There are studies which evaluated environmental impacts in different countries in order to examine the effects of the electricity mix of a country and fabrication processes.
- PV-module fabrication and material-manufacturing processes are responsible for the major part of the environmental impacts of the whole system.
- The life-cycle emissions of PV plants (involving BOS) are remarkably lower in comparison to conventional systems for electricity generation.
- The EPBTs of PV plants are considerably lower than their lifespans, verifying that these systems are sustainable.
- The lifespan is around 10–15 years for an inverter and approximately 25 years (or longer) for a PV system.
- PV plants with tracking are interesting (from an energetic point of view; from an environmental point of view).
- Different climatic conditions were examined.

BIPV systems without involving solar concentration

BIPVs offer aesthetically pleasing systems/buildings [49]. In the literature on PV LCA, there are a few studies which evaluated BIPV systems, taking into account BOS. Perez et al. [49] conducted an LCA study on façade-integrated PVs (mono-Si PV cells; Solaire Building; New York City). In the case of the realistic scenario (EPBT: 3.8 years), around 33% of the EPBT was due to the BOS/framing and 67% was because of the laminates. Issues about the BOS in the case of façade-integrated PV systems were discussed. It was highlighted that, in the Solaire array, 85% of the aluminium (framing) involved recycling. The electrical BOS included two types of J-boxes, direct-current disconnects, alternating-current disconnects and inverters [49].

CPV systems

Concentrating solar systems offer advantages comparing to the non-concentrating ones [17]. Fthenakis and Kim [50] conducted an LCA of a high-concentrating PV plant (Amonix 7700) in Phoenix (AZ, USA). The EPBT of the system (Phoenix, AZ) was calculated to be 0.9 years and its GHG emissions were found to be 27 g $CO_{2.eq}$/kWh (for 30 years). Components such as inverter, tracker, frames and cables were taken into account. Additional CPV LCA studies were presented by Kim and Fthenakis [51], Menoufi et al. [14], Sandwell et al. [52], Lamnatou et al. [53–55]. However, there is a need for more investigations that examine strategies to improve CPV environmental profile. For instance, in the case of CPVs for large-scale applications, components such as trackers and support structures involve large amounts of materials that can be recycled [17].

CdTe PV systems

CdTe is a fast-growing commercial thin-film technology but Te is scarce and cadmium is a carcinogen and highly toxic [56]. In Table 3, investigations about CdTe PV systems are presented. The results show that:

- In certain cases, due to the lack of data for BOS of CdTe PV systems, data for BOS of Si-based PV systems were considered.
- BOS contribution to the total impact is influenced by factors such as the amount of materials needed for foundations and structures.
- Some studies used the electricity mix of a certain country as a reference for comparisons with PV environmental impacts.
- The life-cycle impacts due to solar trackers are mainly associated with the mounting structures.
- BOS impact is higher in the case of systems with trackers but this additional impact is counterbalanced.
- Recycling of BOS materials offers considerable environmental benefits.
- The major part of the impact of a PV system is due to PV material manufacturing.
- Different climatic conditions/locations were evaluated.

Table 2
Studies which present/discuss BOS environmental profile: Si-based PV systems without involving solar concentration. Emphasis: power plants.

Study	System	Location	Materials and components (placing emphasis on BOS)	Environmental issues, methods, indicators	Findings
Fthenakis and Kim [6]	BOS of a 3.5-MW_p poly-Si PV power plant	USA	Various pieces of the BOS	Primary energy, EPBT, GHG emissions, etc.	Total primary energy (BOS life-cycle): 542 MJ/m^2 of installed PV panel; BOS EPBT: 0.37 years; BOS $CO_{2.eq}$ emissions: 7 g/kWh
Mason et al. [43]	BOS of a PV power plant (3.5 MW_p; poly-Si)	USA	BOS: Frames, support structures, wires, concrete, inverters, etc.	Primary energy demand, EPBT, GHG emissions, etc.	BOS life-cycle impacts: 526–542 MJ/m^2; 29–31 kg $CO_{2.eq}$/m^2
Bayod-Rújula et al. [44]	Grid-connected PV plants: 2-axis tracking vs fixed modules (poly-Si)	Spain; Germany	BOS: Support structure, wiring, inverter, etc.	Eco-indicator 99, GWP, CED, etc.	PV plants with tracking are more interesting from an energetic point of view (comparing to PV plants with fixed modules)
Desideri et al. [45]	A ground-mounted 1778.48 kW_p PV plant (poly-Si)	Italy	BOS: Support structures, inverters, transformers, cabling, etc.	Eco-indicator 99, GWP, primary energy, EPBT, etc.	Life-cycle emissions of the PV plant: 0.106 kg $CO_{2.eq}$/kWh
Nian [46]	A 1000-kW_p PV plant (poly-Si)	France, Australia, etc.	BOS: Inverters, transformers, mounting structures, etc.	CO_2 emissions; water and other non-energy inputs, etc.	The major part of the total impact was due to material manufacturing of the PV modules
Hou et al. [47]	A large-scale Si-based PV plant	China	BOS: Mounting structures, inverters, cabling, etc.	GHG emissions, EPBT, etc.	Recycling (aluminium frames; steel components; cabling; inverters) offers environmental benefits
Wu et al. [48]	A poly-Si PV plant (1 MW; on-grid; ground-mounted)	China	BOS: Support structures, cables, inverters, etc.	Energy input/output, EPBT etc.	EPBT: 2.3 years

Table 3
Studies which present/discuss BOS environmental profile: CdTe PV systems.

Study	System	Location	Materials and components (placing emphasis on BOS)	Environmental issues, methods, indicators	Findings
Held and Ilg [57]	CdTe PV plants in Europe	Europe	BOS: cables, inverter, support structures, etc.	CML 2001, primary energy demand, EPBT, etc.	BOS was responsible for around 35–45% of the PV-plant total impact
Sinha and de Wild-Scholten [58]	PV plant 550 MW_{ac} (CdTe)	USA	BOS: Mounting, cabling, inverters, transformers, etc.	$CO_{2.eq}$ emissions, EPBT, etc.	BOS impact: 4–6 g $CO_{2.eq}$/kWh
Sinha et al. [59]	PV plant 550 MW_{ac} (CdTe)	USA	BOS: Mounting, cables, inverter, transformer, etc.	CED, EPBT, $CO_{2.eq}$ emissions, etc.	BOS impact is higher for the systems with trackers but this additional impact is counterbalanced
Kim et al. [60]	100 kW_p CdTe power plants	Malaysia	BOS: Support structure, cabling, frames, etc.	$CO_{2.eq}$ emissions, energy inputs, fossil-fuel consumption, EPBT, CO_2 PBT, etc.	PV-system life-cycle emissions: 15.1 g $CO_{2.eq}$/kWh (7.23 g $CO_{2.eq}$/kWh → due to the PVs; 4.41 g $CO_{2.eq}$/kWh → due to the BOS)
Bergesen et al. [61]	Copper indium gallium selenide and CdTe PV plants	USA	BOS: Module supports, wiring, inverters, transformers, etc.	U.S. Environmental Protection Agency's TRACI 1.0 method; ReCiPe	BOS recycling offers environmental benefits

OPV systems

OPV cells are emerging technologies which offer lightweight, semi-transparent and flexible PV modules [15,18]. In the literature on OPV LCA, there are a few studies which presented information about the BOS of this technology. Espinosa et al. [15] noted that OPV modules do not need a frame. What is needed is attachment to a structure. In the LCA study by Espinosa et al. [15], the PV panels were mounted on a wood structure. Wiring, fuses and monitoring devices were taken into account. Espinosa et al. [62] presented data for the BOS components of OPV installations. Roes et al. [18] conducted an LCA of OPVs. The main goal was the comparison of OPVs (polymer-based) with Si-based PV technologies. The BOS data were taken from de Wild-Scholten et al. [63].

Quantum-dot PV systems

Quantum-dot solar cells can increase the maximum thermodynamic conversion efficiency of solar photon conversion by means of hot photo-generated carriers [64]. Şengül and Theis [65] conducted an LCA of nano-photovoltaic, quantum-dot PV technology, taking into account BOS (data: Mason et al. [43]). The main part of the CED impact was due to PV-module and solar-cell production, followed by the BOS (21%). It was noted that, in the literature on BOS for PVs, there are considerable differences between the life-cycle inventories (e.g. in terms of the steel needed for ground-mounted systems).

Dye-sensitised PV systems

Dye-sensitised solar cells achieve production of electricity by the absorption of a photon by a dye molecule [66]. Greijer et al. [67] evaluated the environmental profile of nanocrystalline dye-sensitised PVs (system: 500 MW; Africa). A life-cycle impact of 19–47 g CO_2/kWh was found. The major part of this impact was related to PV-cell material manufacturing, followed by the production of the additional components of the PV system (frames, junction box, etc.). Details about the inventory related to cabling, frame and junction box are given [67]:

- Cabling: Polyvinyl Chloride (PVC) 0.072 kg per m^2 of active solar-cell area
- Cabling: Copper 0.8 kg per m^2 of active solar-cell area
- Frame: Aluminium 2.1277 kg per m^2 of active solar-cell area
- Junction box: Polyester 0.489 kg per m^2 of active solar-cell area
- Junction box: Silicon rubber 0.042 kg per m^2 of active solar-cell area

Moreover, Veltkamp and de Wild-Scholten [68] investigated dye-sensitised PV cells for large-scale applications. The EPBTs were calculated to be 0.6, 0.8 and 1.3 years: for high, medium and low irradiation, respectively. The GHG emissions varied between 20 and 120 g $CO_{2.eq}$/kWh and it was noted that this impact is strongly influenced by the lifespan of the PV panels.

Comparisons between grid-connected rooftop and ground-based PV systems

On the basis of the results of the study by de Wild-Scholten et al. [63], in-roof systems present lower BOS impacts (in comparison to on-roof and ground-based configurations) because of the credit due to the avoided ceramic roof tiles. The BOS of an in-roof system was responsible for 3% of the total GHG emissions of the whole PV system whereas the BOS (with frames) of an on-roof system was responsible for approximately 18% of the total GHG emissions of the whole PV system. The BOS (with frames) of ground-based installations presented percentages 16–23% (in relation to the total emissions of the whole PV system) [63].

PVT systems without solar concentration

PV systems which combine PV modules and thermal units are known as hybrid PVT systems [4,10]. Tonui and Tripanagnostopoulos [69] investigated PVT modules which included modifications (metallic sheet; fins) of the reference one. The additional components (sheet; fins) have an environmental impact but this is counterbalanced since the modified systems show better performance.

In the case of PVT/water (PVT systems; working fluid: water), hot-water storage tank is important. In the review article by Lamnatou et al. [70], details about the environmental impacts of water storage tanks and other types of storage systems were presented. In certain cases, storage tanks are combined with components such as heaters for auxiliary heating, heat exchangers and heat pumps [70].

Cpvt

A CPVT system combines CPV technology with a thermal unit. In the LCA study by Lamnatou et al. [71], data for the components of a BA CPVT system were presented (France; geometrical concentration ratio 13× (approximately)). The additional components of the PVT system involved: a storage tank of 300 L capacity, pumps, lead-acid batteries, support structure, tubes, etc.

Li et al. [72] studied a CPVT/water system with air–gap-lens-walled compound parabolic concentrator (ALCPC) (geometrical concentration ratio: 2.4×) and a 20-L water storage tank, suitable for BI applications. The ALCPC-PVT system was compared with a non-concentrating PVT one.

Reflectors have an additional impact but, taking into account the life-cycle performance of a solar system, this additional impact is counterbalanced and the use of reflectors offers solar systems (e.g. CPV, CPVT) with better environmental profiles [4].

LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)

On the basis of the data that have been presented in Section "BOS – additional components for PV and PVT Systems: Literature review", Section "LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)" sets out to evaluate the environmental profiles of certain materials related to traditional PV systems for buildings. The analysis has been based on LCA.

Methods and environmental indicators

The LCA has been conducted according to ISO 14040 [73] and ISO 14044 [74]. The functional units and boundaries depend on the case study. The environmental impacts due to material manufacturing have been evaluated.

The vast majority of the calculations have been performed using SimaPro 8 software [75] and ecoinvent 3 database [76], based on IPCC 2013 GWP 100a, CED, ReCiPe and USEtox. IPCC 2013 offers information about GWP. CED is associated with energy resources. Concerning ReCiPe endpoint/single-score, the environmental impact is presented by means of Points (Pts). ReCiPe endpoint/with characterisation is based on Disability-Adjusted Life-Year (DALY) and (species.yr): damage to human health and ecosystems, respectively. In the case of ReCiPe, the perspective H (hierarchist) has been used. With regard to USEtox, the results are based on CTU_h (impact on human health) and CTU_e (impact on ecosystems) [77]. In certain cases, EC and EE [78] with/without involving recycling have also been used.

In the case of BOS components (conventional PV systems), the proposed LCA model includes the following steps: LCI → SimaPro/ecoinvent [75,76] or ICE [78] → evaluation of the impacts due to material manufacturing (with/without recycling) → interpretation of the results → comparisons. In the case of avoided impacts (OPV systems), the steps are as follows: Case study (a PV system based on OPV modules) → PV output (Mediterranean countries) → avoided impacts - Simapro/ecoinvent [75,76] (different electricity mixes: Spain; Italy; Portugal) → comparisons.

BOS materials for PVs: Environmental impacts

GWP and energy demand: Comparisons

The analysis of subsection "GWP and energy demand: Comparisons" is based on data from Raugei et al. [31] (subsection "Si-based PV systems without involving solar concentration - Emphasis: Buildings") and Greijer et al. [67] (subsection "Dye-sensitised PV systems"). In Table 4 the results of the present study as well as findings of other studies are presented. It can be noted that:

- Different types of systems/applications were studied.
- In most cases, typical Si-based PV systems with additional components such as support structures, frames, inverters and cabling were examined.
- Different databases were used.
- Some studies evaluated the effect of recycling.
- In certain cases, there is a good agreement between the findings of the present study and those of the literature about BOS of PV systems.
- The BOS impacts range from 6 to 181 kg $CO_{2.eq}/m^2$ of PV module and from 55 to 1900 MJ_{prim}/m^2 of PV module, depending on the scenario.
- By involving metal recycling, a considerable reduction in the impacts can be achieved.

EC, EE and the effect of recycling

Subsection "EC, EE and the effect of recycling" presents BOS impact per m^2 of PV module (a typical grid-connected PV rooftop system; data from Raugei et al. [31]: subsection "Si-based PV systems without involving solar concentration - Emphasis: Buildings"). The calculations have been based upon ICE database [78], taking into account that ICE offers information about the environmental impacts of materials with/without recycling. In the present study, scenarios with/without recycling have been examined. In Fig. 1 the findings based on EC (kg $CO_{2.eq}$ per m^2 of PV module) and EE (MJ_{prim} per m^2 of PV module) are illustrated. EC values (Fig. 1a) range from 15 to 181 kg $CO_{2.eq}/m^2$. Taking into account that the amounts of copper and aluminium are considerably lower in comparison to the kilogrammes of steel, involving copper and aluminium recycling does not offer a remarkable reduction in the total impact of the whole BOS. On the contrary, steel recycling significantly reduces the EC of the whole system. Steel recycling offers a reduction of 151 kg $CO_{2.eq}$ per m^2 of PV module. Fig. 1b presents primary energy demand. The values range from 294 to 1716 MJ_{prim}/m^2. For the reasons that have been previously discussed, steel recycling offers an appreciable reduction (more than 1000 MJ_{prim}/m^2) in the EE of the whole system.

Multiple LCIA methods and environmental indicators: Primary materials

Subsection "Multiple LCIA methods and environmental indicators: Primary materials" presents the environmental profile of a BOS of a typical grid-connected PV rooftop installation [31]. It has been assumed that the solar system has 60 PV modules (total surface of the PV modules: 99 m^2) which are mounted on a flat surface. The evaluation includes multiple LCIA methods and environmental indicators, based on primary materials [75,76].

With regard to CED, a total primary energy demand of 166 GJ_{prim} has been found. According to ReCiPe endpoint/with characterisation, the total scores are as follows: 4.4E-02 DALY and 1.2E-04 (species.yr). For CED, DALY and (species.yr), steel is the material with the highest impacts, showing percentages which range from 78% to 80%.

Regarding ReCiPe midpoint/with characterisation (Fig. 2a; contribution of each material), the component with the lowest percentages (less than 0.2%) is PVC whereas the one with the highest percentages (59–99%) is steel.

Fig. 2b shows the findings based on Ecological footprint single-score. Carbon dioxide shows considerably higher scores in comparison to the other two impact categories. Considering Carbon dioxide, Nuclear and Land occupation, steel is the material with the highest impacts, showing scores which range from 1486 to 25114 Pts.

Concerning USEtox/with characterisation, the total impacts are as follows: 1.1E-06 CTU_h for Human toxicity/cancer, 7.7E-08 CTU_h for Human toxicity/non-cancer and 58 CTU_e for Ecotoxicity. Steel is the component with the highest percentages (89–95%). Aluminium shows percentages which range from 4% to 10%. On the other hand, copper and PVC components present percentages which are lower than 1%.

Comments about the results

The present analysis (subsections "GWP and energy demand: Comparisons", "EC, EE and the effect of recycling" and "Multiple LCIA methods and environmental indicators: Primary materials") has been based on certain data which involve large amounts of steel (Raugei et al. [31]; subsection "Si-based PV systems without involving solar concentration - Emphasis: Buildings"). PV support structure is a critical component (from different points of view: environmental, economic, etc.) and there are studies which compare different materials. For example, steel vs aluminium [32]. Therefore, an alternative scenario would be a BOS that is mainly based on aluminium. Certainly, in this case, the results/conclusions would be different.

Table 4
BOS and, in general, additional components related to different types of PV systems. GWP and energy demand: Results of the present study; results of other studies.

References	GWP	Energy demand	Databases	Components (placing emphasis on BOS)	Type of PV system	Additional information/ comments
Present study (data from Raugei et al. [31])	135 kg $CO_{2.eq}/m^2$ of PV module	1672 MJ_{prim}/m^2 of PV module	ecoinvent	Frame, support structure, cables and contact boxes	Typical grid-connected rooftop PV systems	- IPCC 2013 GWP 100a- CED- Primary materials
Present study (data from Raugei et al., [31])	181 kg $CO_{2.eq}/m^2$ of PV module	1717 MJ_{prim}/m^2 of PV module	ICE	Frame, support structure, cables and contact boxes	Typical grid-connected rooftop PV systems	- EC- EE- Primary materials
Present study (data from Raugei et al., [31])	15 kg $CO_{2.eq}/m^2$ of PV module	294 MJ_{prim}/m^2 of PV module	ICE	Frame, support structure, cables and contact boxes	Typical grid-connected rooftop PV systems	- EC- EE- Involving aluminium, steel and copper recycling
Present study (data from Greijer et al., [67])	41 kg $CO_{2.eq}/m^2$ of active solar cell area	466 MJ_{prim}/m^2 of active solar cell area	ecoinvent	Cabling, frame, junction box	Large-scale PV applications	- IPCC 2013 GWP 100a- CED- Primary materials- Module area per 1 m^2 of active solar cell area = 1.43 m^2 [67]
Present study (data from Greijer et al., [67])	32 kg $CO_{2.eq}/m^2$ of active solar cell area	547 MJ_{prim}/m^2 of active solar cell area	ICE	Cabling, frame, junction box	Large-scale PV applications	- EC- EE- Primary materials- Module area per 1 m^2 of active solar cell area = 1.43 m^2 [67]
Present study (data from Greijer et al., [67])	6 kg $CO_{2.eq}/m^2$ of active solar cell area	114 MJ_{prim}/m^2 of active solar cell area	ICE	Cabling, frame, junction box	Large-scale PV applications	- EC- EE- Involving aluminium and copper recycling- Module area per 1 m^2 of active solar cell area = 1.43 m^2 [67]
Frankl et al. [29]		500–1900 MJ_{prim}/m^2: approximate values (scenario: present)	Several databases	BOS (steel, aluminium, concrete, copper, PVC, clay)	A PV plant and different kinds of PV systems for buildings	- Primary energy content- Primary aluminium
Frankl et al. [29]		200–700 MJ_{prim}/m^2: approximate values (scenario: optimised)	Several databases	BOS (steel, aluminium, concrete, copper, PVC, clay)	Different kinds of PV systems for buildings	- Primary energy content- Primary and secondary aluminium
Alsema and Nieuwlaar [79]		500 MJ/m^2	Not directly stated	Array support: scenario 2020	Roof-integrated PV system	- Energy requirements- Issues about recycling were discussed
Alsema and Nieuwlaar [79]		400 MJ_{prim}/m^2 of module area	Not directly stated	Module frame (aluminium)	Typical poly-Si PV module	- Energy requirements- Issues about recycling were discussed
Fthenakis and Kim [6]		542 MJ_{prim}/m^2 of installed PV module	ecoinvent, USLCI, etc.	BOS (total; various pieces)	PV plant	- Total primary energy- It was noted that further investigation (LCA) on CdTe recycling is necessary
Fthenakis and Kim [6]		331 MJ_{prim}/m^2 of installed PV module	ecoinvent, USLCI, etc.	Frame (total)	PV plant	- Total primary energy- It was noted that further investigation (LCA) on CdTe recycling is necessary
Alsema and de Wild-Scholten [35,36]	6 kg $CO_{2.eq}/m^2$ (approximately)	100 MJ_{prim}/m^2	ecoinvent	Array support, cabling	Grid-connected roof-top PV system	- IPCC 2001 GWP 100a- CED- The use of secondary (recycled) materials in order to improve BOS environmental profile was discussed
Alsema and de Wild-Scholten [35]		236 MJ_{prim}/m^2	ecoinvent	Frame of a poly-Si PV module	Grid-connected roof-top PV system	- CED– 1 m^2 of module area = 0.92 m^2 of wafer area
Mason et al. [43]	29–31 kg $CO_{2.eq}/m^2$ (depending on the scenario)	526–542 MJ_{prim}/m^2 (depending on the scenario)	Franklin, ecoinvent, NREL US LCI, Aluminium Association LCI, etc.	Frames for the PV modules, support structure, wires, concrete, inverters, transformers, etc.	PV plant	- $CO_{2.eq}$ emissions- EE- Different scenarios (primary materials, recycling, etc.) were examined
Pacca et al. [38]	17 kg $CO_{2.eq}/m^2$ (approximately)	242 MJ_{prim}/m^2	Databases from SimaPro (Franklin and so on)	Support structure, wires, inverter, transportation, installation	Roof-added PV system	- $CO_{2.eq}$ emissions - Energy consumption
Espinosa et al. [62]		55 MJ_{prim}/m^2 (approximately)	ecoinvent and so on	Support structure	OPV modules: park installation	- CED- Issues about silver recycling were discussed
Espinosa et al. [62]		97 MJ_{prim}/m^2 (approximately)	ecoinvent and so on	Support structure	OPV modules: balloon-type installation	- CED- Issues about silver recycling were discussed
Wu et al. [48]		270 MJ_{prim}/m^2	Not directly stated	Frame	PV plant	- Primary energy inputs
Wu et al. [48]		100 MJ_{prim}/m^2	Not directly stated	Support structure, cabling	PV plant	- Primary energy inputs

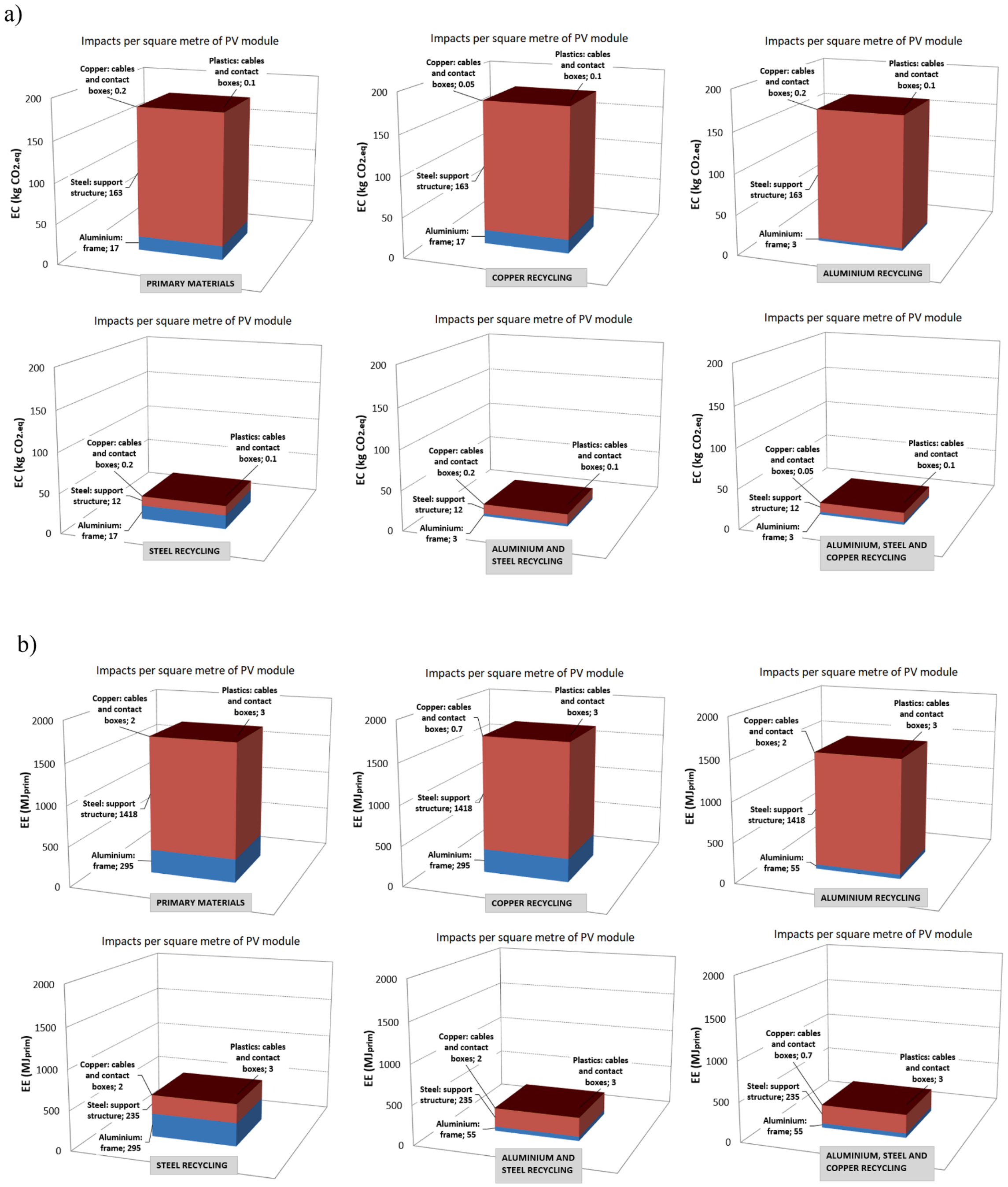


Fig. 1. BOS of a typical grid-connected PV rooftop system: a) EC (kg $CO_{2.eq}$) per m^2 of PV module, b) EE (MJ_{prim}) per m^2 of PV module, based on ICE database [78]. Data: Raugei et al. [31]. Functional unit: BOS components/materials of a grid-connected PV rooftop system; impact per m^2 of PV module.

PV systems that use small amounts of BOS materials – Avoided environmental impacts – A case study of OPVs – Present study (Results and Discussion)

Taking into account the environmental impacts related to the BOS of traditional PV systems (Section “LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)”), Section “PV systems that use small amounts of BOS materials – Avoided environmental impacts – A case study of OPVs – Present study (Results and Discussion)” sets out to present an emerging PV technology that needs considerably lower amounts of BOS materials (in comparison to traditional PV installations with frames, support structures, etc.). This burgeoning technology is known as OPV (subsection “OPV systems”).

OPV modules are lightweight and flexible [15,18] and require, therefore, much less BOS materials (comparing to traditional PV installations). The goal of Section “PV systems that use small amounts of BOS materials – Avoided environmental impacts – A case study of OPVs – Present study (Results and Discussion)” is to analyse the avoided environmental impacts due to the use of the electricity produced by an OPV system instead of using the electricity mix of a certain country. The analysis has been based upon a theoretical OPV system for buildings. It has been assumed that the annual OPV output ranges from 1965 to 2035 kWh/year (Mediterranean climate: Spain, Italy and Portugal). According to the literature on OPV systems [80,81], this assumption is logical.

The avoided environmental impacts of the proposed OPV system

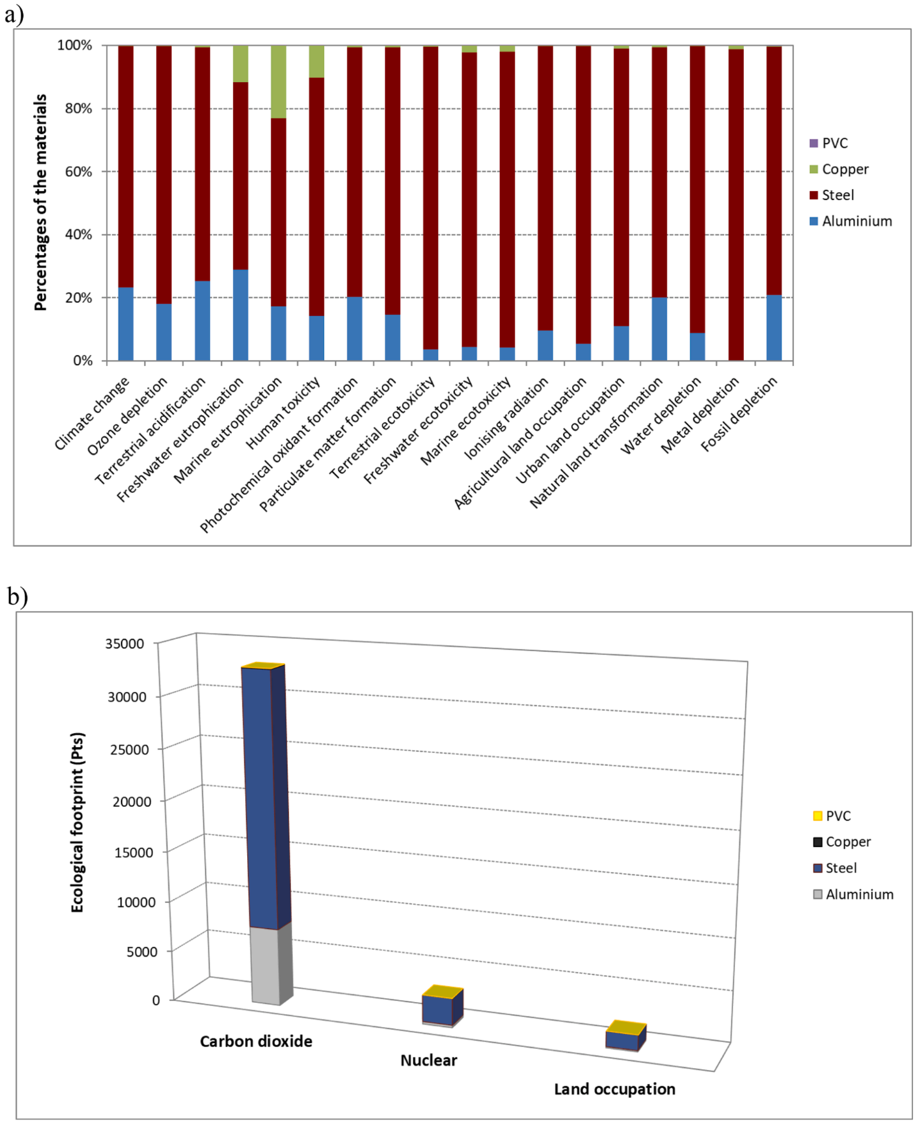


Fig. 2. BOS of a PV system with 60 panels mounted on a flat-surface: a) ReCiPe midpoint/with characterisation (percentages of each material), b) Ecological footprint single-score (Pts). Functional unit: BOS components/materials of a PV system with 60 panels.

have been evaluated based on different electricity mixes: Spain; Italy; Portugal. The study involves: IPCC 2013 GWP 100a, CED, ReCiPe (endpoint; single-score), USEtox (CTU_h; CTU_e) and Ecological footprint (single-score) [75,76].

In Fig. 3a and b, GWP and CED findings are presented. It can be seen that, by using the electricity mixes of Italy and Portugal, higher avoided GHG emissions can be achieved (Fig. 3a). The GWP differences between Spain and Italy/Portugal range from 200 to 288 kg $CO_{2.eq}$ per year. In terms of CED (Fig. 3b), the electricity mixes of Spain and Italy offer 2.3–3.3 GJ_{prim}/year higher avoided CED impacts (in comparison to the one of Portugal).

ReCiPe endpoint/single-score findings reveal that the electricity mixes of Italy and Portugal offer higher avoided impacts (in comparison to the one of Spain). These differences range from: i) 8 to 9 Pts/year for Human Health, ii) 4 to 5 Pts/year for Ecosystems, iii) 4 to 10 Pts/year for Resources.

Regarding USEtox/with characterisation, in the case of Human toxicity/cancer, by using the electricity mixes of Italy and Portugal higher avoided impacts can be achieved. Concerning Human toxicity/non-cancer: i) the electricity mixes of Spain and Portugal present almost the same avoided impacts (around 8.0E-09 CTU_h/year), ii) the one of Italy offers higher avoided impacts (around 2.0E-08 CTU_h/year).

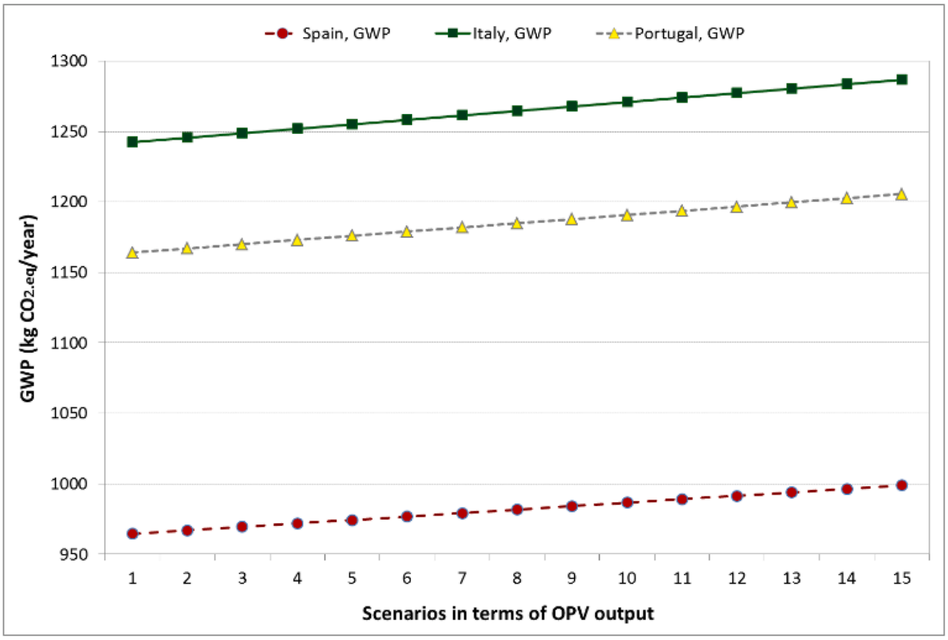
The results in terms of Ecotoxicity reveal that the electricity mixes of Spain and Portugal have approximately the same avoided impacts (around 8–9 CTU_e/year) whereas the one of Italy presents avoided impacts which range from 23 to 24 CTU_e/year.

Ecological footprint/single-score results show that: i) carbon dioxide/avoided impacts range from 2360 (Spain) to 3113 (Italy) Pts/year, ii) based on the impact category of Nuclear, the use of the electricity mix of Spain offers avoided environmental impacts which are remarkably higher in comparison to those of the electricity mixes of Italy and Portugal, iii) in terms of Land occupation, the avoided impacts range from 33 (Spain) to 58 (Portugal) Pts/year.

Generally speaking, the results (avoided environmental impacts) are promising. However, it should be noted that a major drawback of OPV modules is that their lifespans are short comparing to traditional PV technologies [15,62,81].

OPV greenhouses: Critical factors – Literature review

Taking into account the impacts related to traditional PV systems (Section “LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)”) and the advantages of OPV solar cells (Section “PV systems that use small a)



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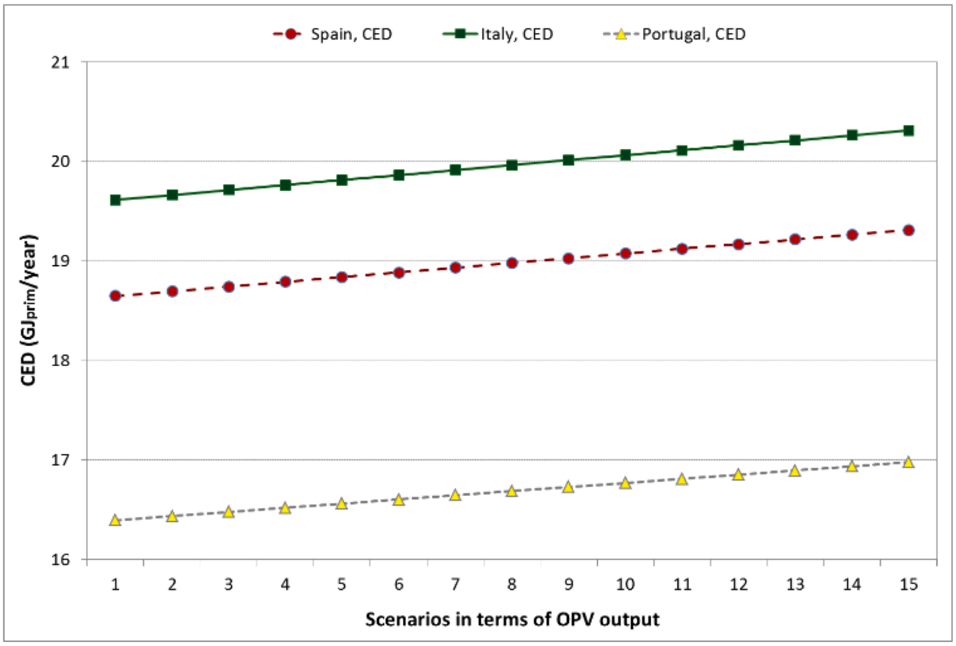

Fig. 3. The avoided environmental impacts (due to the use of the proposed OPV system instead of using the electricity mix of a certain country) based on: a) GWP 100a (kg $CO_{2.eq}$/year), b) CED (GJ_{prim}/year). The graphs show the avoided impacts vs the output of the proposed OPV system (kWh/year). The analysis includes different electricity mixes: Spain; Italy; Portugal. Scenarios 1–15 refer to values which range from 1965 to 2035 kWh/year.

amounts of BOS materials – Avoided environmental impacts – A case study of OPVs – Present study (Results and Discussion)”), Section “OPV greenhouses: Critical factors – Literature review” sets out to present information about OPV greenhouses.

OPVs for greenhouses have gained attention in recent years. The literature review of OPV greenhouses shows that, during the last two years, a great number of studies have been conducted. In Table 5 publications on greenhouses, placing emphasis on OPV greenhouses, are presented. Considering the results of Table 5 as well as those of other studies, it can be seen that:

- Overall, there are a handful of articles about OPV greenhouses.
- Most OPV-greenhouse studies examined common greenhouse crops and it is, therefore, necessary to investigate a wider variety of plants.
- There is a dearth of LCA studies on OPV greenhouses.
- OPV greenhouses do not need additional components such as support structures and frames which are necessary in the case of greenhouses with traditional Si-based PV modules [91].
- Active-layer OPVs with strong NIR absorption and visible-light transmittance for greenhouse shading offer multiple advantages: they are flexible; they have low CO_2 emissions; they have short energy payback times, etc. [92].
- It would be a great idea to develop OPV greenhouses with smart systems. Gruda et al. [93] addressed the concept of smart greenhouses.

Table 5
Studies on greenhouses, placing emphasis on OPV greenhouses.

Study	Type of study	Goals	Greenhouse type	Plants	Location	Findings – suggestions
Emmott et al. [82]	Research paper (modelling)	To investigate spectral selectivity and present a techno-economic analysis	OPV greenhouse	27 herbaceous plants (common greenhouse crops; tomato, lettuce, cucumber)	Spain	Crops such as basil and tropical flowers could tolerate lower levels of transparency
Yang et al. [83]	Research paper (modelling)	To evaluate OPV transmission and absorption	OPV greenhouse	Crops	–	The proposed configuration achieved optimisation of daylight utilisation (tandem photonic crystals; light manipulation)
Ercilla-Montserrat et al. [84]	Research paper (experimental)	Assessment of aerobiological air quality	Rooftop greenhouse (BI agriculture; urban agriculture)	Tomato	Spain (near Barcelona)	Measures to reduce/control indoor bioaerosols are important
Teranaka et al. [85]	Research paper (modelling)	To simulate solar radiation	OPV greenhouse	Tomato	Japan (Kizugawa city, Kyoto)	A PV-installation plan was proposed
Okada et al. [86]	Research paper (modelling)	Evaluation of crop production and energy generation	OPV greenhouse	Lettuce	USA (Arizona)	The predicted fresh shoot weights were comparable to those of other studies
Zisis et al. [87]	Research paper (modelling; experimental)	To study the effects on plant growth	OPV greenhouse	Pepper plants	Greece (Thessaloniki)	OPV shading effect was found to be beneficial to the plants
Magadley et al. [88]	Research paper (modelling; experimental)	Assessment of OPV outdoor behaviour (OPVs on a greenhouse roof)	OPV greenhouse	Crops	Israel (Kfar Qara)	Diurnal variation in OPV behaviour was studied
La Notte et al. [89]	Review	To present an overview of OPV and other PV technologies for greenhouses	Greenhouses with OPVs and other types of PV technologies	Different types of plants	Different locations	There are new PV technologies which are promising because they tune their spectral properties
Ravishankar et al. [21]	Research paper (modelling)	To achieve Net Zero Energy greenhouses	Net Zero Energy greenhouses with OPVs	A variety of crops	USA (Phoenix, AZ, Raleigh, NC and Antigo, WI)	Semi-transparent OPVs effectively replace shade cloths
Waller et al. [25]	Research paper (modelling; experimental)	To evaluate a greenhouse with OPVs for hydroponic tomato production	OPV greenhouse	Tomato	USA (Arizona)	The adoption of semi-transparent OPV modules for seasonal shading (high-light region) is feasible
Meitzner et al. [24]	Essay	To evaluate the connection between agrivoltaics and OPVs	OPV greenhouses and polytunnels	Crops	Semi-arid and arid regions	OPVs for greenhouses and polytunnels could be a key factor in OPV-market development
Ravishankar et al. [26]	Research paper (modelling; experimental)	To balance crop yield and energy harvesting in OPV greenhouses	OPV greenhouse	Lettuce	USA (Sacramento, California)	Factors such as fresh weight and chlorophyll content of the plants grown under OPV filters were examined
Friman-Peretz et al. [27]	Research paper (experimental)	To evaluate the effect of non-homogeneous shading (semi-transparent OPVs)	OPV greenhouse tunnel	Tomato	Israel (Kfar Qari)	OPV tunnel (cloudy days): the spatial variability of radiation in the tunnel was found to be smaller (comparing to sunny days)
Song et al. [90]	Research paper (modelling; experimental)	To study the relationship between herbal photosynthetic growth and OPVs	OPV greenhouse	Medicinal plants	China	The plants grown under ultra-flexible light-permeable OPVs presented growing tendency and pharmaceutical value comparable to the plants grown under direct sunlight

- Greenhouse covering materials should fulfil certain criteria related to available PAR distribution at crop level, airflow patterns, vertical temperature gradient, etc. [94].
- The application of opaque dye-sensitised solar cells is limited; this issue is associated with the compatibility with crop growth [95]. Organic dyes for dye-sensitised solar cells for greenhouse claddings were investigated [96].
- It would be interesting to develop OPV greenhouses with passive solar heating systems → Goal: to achieve energy savings [97].
- It is important to study OPV spectral selectivity, transmission and absorption [82,83], spectral properties and other parameters [89].
- Key factors are related to aerobiological air quality [84], non-homogeneous shading [27], solar radiation [85], crop production and energy generation [86,26], OPV outdoor behaviour (OPVs on greenhouse roof) [88], hydroponic greenhouses [25], shading and plant growth [87], polytunnels [24], techno-economic analysis [82], etc.
- In the case of medicinal plants, growth and pharmaceutical value [90] are critical factors.
- Zero energy greenhouses [21] and BI/rooftop greenhouses [84] are burgeoning concepts.

PV systems and challenges: A discussion based on the present study and the literature on PV

PV systems are eco-friendly on the grounds that they have low GHG emissions (considerably lower in comparison to conventional energy systems) and EPBTs which are remarkably lower comparing to PV life-spans [7]. The analysis of Section "LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)" shows that traditional PV installations have some BOS components which have high environmental impacts. However, by involving metal recycling, an appreciable reduction in these impacts can be achieved. Moreover, in Section "PV systems that use small amounts of BOS materials – Avoided environmental impacts – A case study of OPVs – Present study (Results and Discussion)" an alternative solution is proposed: use of burgeoning PV systems which need small amounts of BOS materials (OPV systems). On the other hand, Section "OPV greenhouses: Critical factors – Literature review" presents key factors related to OPV greenhouses, highlighting the importance of agrivoltaics based on OPVs.

From a wider perspective, energy policy, waste management and the electricity mix of a country play a pivotal role. In light of the results of the present study (sections "LCA – environmental impacts related to BOS materials of conventional PV systems – Present study (Results and Discussion)"–"OPV greenhouses: Critical factors – Literature review"), it can be seen that PVs and sustainable energy systems pose challenges such as: Effective waste management; mitigation of environmental impacts by adopting recycling; recycling laws; reduction in the quantities of materials needed for BOS; use of PV systems (and other types of renewable energy systems) which require small amounts of BOS materials; promotion of emerging technologies (by way of illustration, OPVs for buildings and greenhouses); agrivoltaic applications; development of BI/rooftop greenhouses; adoption of BIPV systems; use of transparent and semi-transparent PV modules; combination of PVs and water heaters (or air heaters); development of eco-friendly storage devices; improvement of the environmental profile of the electricity mix of a country; use of smart energy systems, promotion of PV/smart energy systems and microgrids; implementation of zero-energy buildings; evaluation of the systems based on different markets; energy-transition strategies.

An additional challenge is the development of BOS LCI for a whole host of PV technologies. In subsections "Si-based PV systems without involving solar concentration - Emphasis: Buildings"–"Cpvt", a large number of PV-cell types are discussed. However, a future prospect would be the availability of LCI data for BOS of additional PV technologies such as CIGS (copper indium gallium diselenide), perovskite, bifacial, heterojunction and so on. Generally speaking, PVs pose different types of challenges [98,99].

On the other hand, it would be of great interest to further investigate innovative OPV greenhouses (e.g. greenhouses with OPV/ethylene tetrafluoroethylene modules) and develop models for these systems. For instance, models to address issues such as energy efficiency, environmental profiles, computational fluid dynamics, plant behaviour, pest control, hydroponics, cladding materials, spectral transmittance, bioplastics, energy balance, smart and renewable-energy systems, etc. Another challenge is the development of BI/rooftop greenhouses (e.g. with OPV/ethylene tetrafluoroethylene modules) in order to evaluate parameters such as optimum plant growth, thermal/cooling demand, environmental performance and energy efficiency.

Limitations of the present study and suggestions for future research

A part of the present work is based on data (BOS for traditional PV systems) from Raugei et al. [31]. This inventory has many kilogrammes of steel. An alternative option could be a BOS which has aluminium as the basic material [32]. Certainly, this may influence the results.

The present work (environmental LCA; environmental profiles) would be combined with other types of analysis: from an energetic point of view; from an economic point of view, etc. Different LCA databases would also be used. Furthermore, static LCA vs dynamic LCA would offer interesting results [100].

The case study "OPV – avoided impacts – Mediterranean countries" is about the specific case of OPV systems in Spain, Italy and Portugal. In Mediterranean countries, the high solar-resource availability favours solar systems. Certainly, the adoption of different climatic conditions can influence the results, resulting in lower avoided impacts (for example, in the case of North European countries). The adoption of different electricity mixes (different countries in comparison to the present case study) may also influence the results, depending on the composition of the electricity mix of a certain country.

On the other hand, taking into account the gaps in the literature on PV BOS LCA and the challenges posed by emerging PV technologies, it would be interesting to develop LCA models for BOS of PV technologies such as CIGS, perovskite, bifacial, heterojunction and so on.

Regarding methods and environmental indicators, the present work has been based on EE, EC, IPCC 2013 GWP 100a, CED, ReCiPe and USEtox. In other words, the present study offers information about different types of environmental impacts: related to GHG emissions, energy demand, human toxicity, ecotoxicity, etc. The proposed models would be extended in order to include uncertainty analysis, enabling estimation of confidence intervals for the results.

Moreover, the analysis of subsection "BOS materials for PVs: Environmental impacts" is based on data from Raugei et al. [31] and Greijer et al. [67]. An alternative scenario would be a comparison with recently published BOS data, proposing alternative materials in order to reduce the environmental impacts of the whole system.

Conclusions

The present study sets out to present an environmental LCA of BOS of PV installations and information about OPV cells. To this end: 1) the first part of the article offers an overview of BOS for PVs (literature review), 2) the second part is a case study of the environmental profile of the BOS of a grid-connected PV rooftop system, 3) the third part is a case study of the avoided environmental impacts of PV systems which need small amounts of BOS materials (OPV systems), based on different electricity mixes, 4) the fourth and fifth parts of the paper present critical factors for OPV greenhouses and challenges of PV technologies.

The novelty of the present work lies in the fact that it presents information about the environmental profile of BOS for different types of PV technologies, challenges for PV systems and case studies, based on different types of LCIA methods and environmental indicators.

The results of the present work (literature review and case studies) show that:

- BOS is associated with the type of the PV system and involves different kinds of materials.
- Metal recycling offers a remarkable reduction in the environmental impacts of the BOS of a typical grid-connected PV rooftop system.
- The avoided impacts thanks to the use of PV systems are inextricably linked to the electricity mix of a certain country.
- OPV systems are lightweight/flexible and do not need the BOS components of a typical Si-based PV system: support structures and so on.
- OPVs for greenhouses have gained attention in recent years.
- It is necessary to investigate a wide variety of plants for OPV greenhouses.
- There is a dearth of LCA studies on OPV greenhouses.
- It would be a great idea to develop OPV smart greenhouses, zero energy greenhouses and greenhouses with passive solar heating, taking into account PAR distribution at crop level, air flow patterns, air quality, etc.
- OPV modules have low environmental impacts, offering eco-friendly applications for greenhouses, buildings and so on.

To sum up, the present work has been based on LCA case studies and literature review and the main findings include: the environmental profile of BOS components for different types of PV systems and the importance of using PV technologies (e.g. OPV modules) which do not need heavy BOS components.

Finally, it should be noted that the present study has some limitations and would be extended, including recent PV BOS data, uncertainty analysis, additional databases, different climatic conditions and more PV technologies.

Declaration of Competing Interest

The authors 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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