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Environmental assessment of a BIPV system

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Abstract. The application of Photovoltaic (PV) power in the building sector, is expanding as part of the ongoing energy transition into renewables. The article addresses the question of sustainability of energy generated from PVs through an environmental assessment of a building-integrated PV system (BIPV) connected to the grid through net metering. Employing retrospective life cycle analysis (LCA), with the *CCaLC2* software and *ecoinvent* data, the article shows that the carrying structure and other balance of system (BOS) components are responsible for a three times higher energy payback time than the literature average. However, total environmental impact can be lowered through reuse or reinstallation of PVs on the same building structure after the 30-year interval. Further ways to improve environmental efficiency include identifying the most polluting materials for each LCA parameter. The results of this study are of interest to researchers and producers of PVs and organizations investing and promoting decentralized power production through PVs.

Keywords: building-integrated photovoltaic systems; life cycle analysis; CO_2 emissions; EPBT; sustainability

1. Introduction

Renewable energy systems are a significant technical component in buildings, in the face of growing global electricity demand, especially within non-OECD countries (EIA 2016) where energy generation is a vital subsystem of the overall resource use (Mansoor *et al.* 2019). Expanding renewable energy is set to offset the use of natural non-renewable resources for electricity generation, which have caused environmental crises, such as atmospheric pollution, climate change and depletion of stock resources.

In order to address environmental and energy issues in a combined manner renewable energy sources must work more efficiently and synergistically. Recent studies have discussed combinations of different types of renewables (Carnevale *et al.* 2016), where especially solar energy commands a growing interest due to its abundance and site independence. The most popular form of generating solar power is by means of photovoltaic (PV) elements that convert solar radiation into DC electricity through the photovoltaic phenomenon. The PV systems industry

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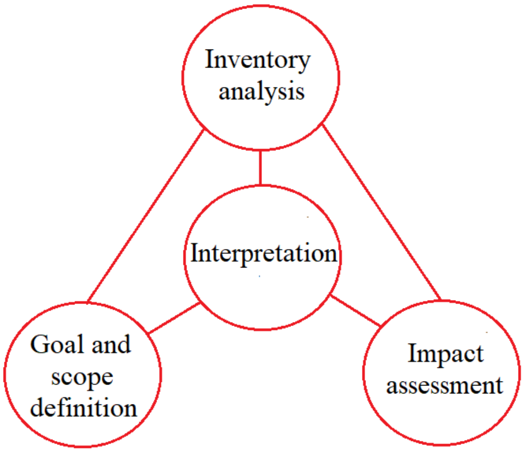


Fig. 1 Framework of life cycle assessment methodology. Source: authors based on Peng *et al.* (2013)

is a rapidly expanding sector (Tripathy *et al.* 2016), with the important advantage of not generating greenhouse gas emissions (GHG) during operation, and ease of installation or integration in buildings, which raises the sustainability of existing infrastructures.

Building-integrated energy production is a promising energy efficiency measure, given the building sector's share in the global CO_2 emissions. For example, out of the European CO_2-eq emissions 35 percent were caused by residential and service buildings (European Commission, 2011; Perez *et al.* (2008). Since up to 80 percent of the buildings that will be occupied by 2050 in Europe, have already been built (The Royal Academy of Engineering, 2010); additional measures are required for improving their energy efficiency. If left unaddressed (Vilches *et al.* 2017), the energy requirements of the existing building stock will be responsible for a large proportion of the European CO_2-eq emissions in the future.

Life cycle analysis (LCA) is a current and useful tool to evaluate the environmental impacts of energy technologies. LCA provides a framework for considering the environmental inputs and outputs of a product, from cradle to grave. It consists of four stages strongly interconnected to each other: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation. (Fig. 1).

LCA analysis of PV systems examines the manufacturing process of silicon-based PV modules. Fig. 2. illustrates the whole process, which begins with silica extraction, goes through the steps of quartz reduction, metallurgical grade silicon (MG-silicon) purification, electronic silicon (EG-silicon) or solar-grade silicon (SoG-silicon) production, mono-Si or multi-Si crystallization, wafer sawing, cell production, and concludes with panel or laminate assembly (Wong *et al.* 2016).

The particular Building-integrated Photovoltaic Systems (BIPVs) application analysed in this article consisted of a skylight and a car shelter. Both of them can be considered a PV shading device (PVSD), with the skylight installed as PV-overhead glazing and the car shelter integrating a PV-sunshade (Frontini *et al.* 2015; Pester and Crick, 2013). In general, there are plenty of studies about BIPV systems, however there are only 43 studies since 1998 about PVSD (Zhang *et al.* 2018). PV car shelters are often used only as charging stations for electric vehicles (EV), either off-grid or on-grid (Kumar *et al.* 2019; Tulpule *et al.* 2013). While the possibility of a charging station was not considered in this paper, however, such an option is possible.

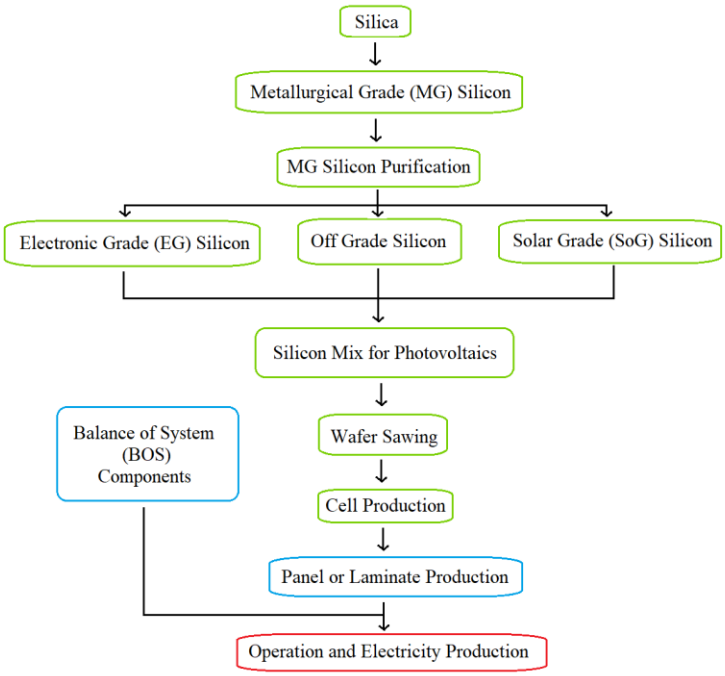


Fig. 2 Silicon PV modules manufacturing line. Source: based on Wong *et al.* (2016)

PV power as a decentralized form of power generation often requires public support and incentives. One example of state promotion is the Indian Solar mission (Shukla *et al.* 2018a), which addresses obstacles such as, lack of finance, incentives, and expertise (Shukla *et al.*2017a). Nevertheless, the installation of PV must be strategically correct, starting at the location where energy is mostly needed. Subsequently, power production optimization must take place to increase the environmental and economic performance of these investments (Sardi *et al.* 2017).

1.1 Environmental performance assessment of BIPV systems

Various tools can be used to analyze the environmental performance of electricity generation from BIPV renewable energy systems. This paper discusses the environmental profile of a BIPV system, mainly through a life cycle analysis (LCA). Additional components are also reviewed, such as the Balance of System Components (BOS), Polycrystalline PV projects and BIPV applications.

1.1.1 Manufacturing and life cycle of polycrystalline PV systems

PV panels, the basic element in BIPV systems, can be manufactured following different production methods. In our experimental project, polycrystalline Silicon-PVs were incorporated in the system, so a literature review of this type of system process is provided here.

A step-by-step understanding of the PV life cycle is necessary to perform the LCAs. During the first step, silica sand is put into an arc furnace to increase its purity to metallurgical grade silicon

(MG-silicon). Subsequently a further purification is required, following the *Siemens* or the modified *Siemens* processes (Fthenakis *et al.* 2008). In the first method, the reaction takes place in temperatures exceeding 1100°C, using the trichlorosilane ($SiHCl_3$) and hydrogen (H_2) gases. The modified version uses silane (SiH_4) and hydrogen (H_2), in temperatures around 800°C. Other techniques, such as *Elkem solar silicon* (ESS), require 66% less energy than the conventional *Siemens* process (Gløckner *et al.* 2008). The product of these processes is referred to as electronic grade silicon (EG-silicon) in the *Siemens* process and solar grade silicon (SoG-silicon) in the modified *Siemens* process. The silicon mix for the PV production comprises the EG-silicon, SoG silicon and off-grade silicon. The latter accounted only for 5% of the global PV supply in 2006, with a further reduction in usage foreseen (Peng *et al.* 2013). This mix, as a feedstock, is then melted and casted into molds. The poly-Si wafer is forthwith produced from these poly-Si blocks/molds. The last stage is sawing of the wafers followed by the production of the PV-cell. During this stage, the cell PV is attached to silver contacts and then encapsulated into the ethyl-vinyl acetate (EVA) which offers protection from external forces. The embedded PV-element is then sandwiched with low-iron glass under heat and pressure and the edges are purified (Jungbluth *et al.* 2012). The final product requires an aluminum frame, except for the case of laminate PV, which can be integrated straight into the building. The longest and more passive stage in the PV life cycle is electricity production. This step lasts between 25 to 30 years (NREL 2012). Following this stage, the PV is no longer usable or inefficient to maintain, and the decommission process begins. This leads to two options. The first option is landfill disposal and the second is recycling. The former is unsustainable; the latter manages electronic waste, minimizing the environmental impact of these products. There are many studies discussing chemical and physical recycling processes of modules or Silicon kerf (Padoan *et al.* 2019, Mesaritis *et al.* 2019, Fiandra *et al.* 2019, Granata *et al.* 2014) that can be used to promote sustainable silicon feedback, for the silicon mix.

1.1.2 Life cycle analyses of polycrystalline PV systems

Most reviews about the LCAs of PV technologies (Sherwani *et al.* 2010; Shukla *et al.* 2017b; Tripathy *et al.* 2016; Peng *et al.* 2013; Wong *et al.* 2016) point to two indices, the Greenhouse Gas emissions (g-CO_2 / kWh) and the Energy Payback Time (EPBT).

Sherwani *et al.* (2010) compared different PV technologies including Amorphous silicon (a-Si),Polycrystalline silicon (p-Si), monocrystalline silicon (Mc-Si), nanocrystalline dye-sensitized (ncDSC) system with other thin film technologies such as Cadmium telluride (CdTe) and copper-indium-selenium (CIS) PVs, concluding that thin film technologies consume less embodied energy, than other PV technologies. GHG and EPBT indices depend upon many factors and neither of them provides a definitive answer regarding the LCA of PVs. Similarly, Peng *et al.* (2013) performed a review with a bigger data set and two extra PV technologies (heterojunction solar cells and high concentration PV). The results were compatible with the previous study, indicating that thin film technologies had less energy requirements and among them CdTe had the lowest environmental impact and the shortest EPBT. Advanced PV systems had almost equal EPBT with the thin film PV, but CO_2 emissions were higher. On the other hand, Tripathy *et al.* (2016) and Shukla *et al.* (2017) made a technical, economic, and environmental review of BIPV systems. Various PV technologies were discussed but the BIPV with the poly-Si technology were considered in this study. From the data presented poly-Si has an environmental profile in-between thin film and mono-Si with thin film, with the latter being the best environmental choice of PV. Wong *et al.* (2016) studied the most prominent PV technologies, which are the mono and poly Si PV. In their study the environmental footprint per production stage was highlighted. The Si-

Table 1 Poly-Si LCAs from bibliography

Authors	Year	Location	Module efficiency (%)	Power rating	Lifecycle (years)	EPBT (years)	GHG emissions (gCO_2eq/kWh)
Ritzen *et al.* **	2017	Netherlands	14.8	5.6 kW	20	3.25 3.56	na
Wang *et al.*	2016	Shanghai	10.8	3 kW	25	4.2	na
Yue *et al.*	2014	South Europe	13.2	na	30	1.6	31.8
Kim *et al.*	2014	Korea	14.9	100 kW	30	3.68	31.5
Desideri *et al.*	2012	Italy	14.4	1778 kW	25	4.17	88.7
Nishimura *et al.*	2010	China	15.8	100 MW	20	1.73	na
Ito *et al.*	2010	Japan	na	100 MW	30	2	43
Zhai and William	2010	South Europe	13.2	na	30	1.4	24
Wild-Scholten	2009	Europe	13.2	na	30	1.75	28
Stoppato	2008	Italy	16	na	28	3.7	569
Stoppato	2008	Italy	16	na	28	4.8	569
Ito *et al.*	2007	China	12.8	100 MW	30	1.9	12.1
Ito *et al.*	2007	China	15.8	100MW	30	1.5	9.4
Pacca *et al.*	2006	United States	12.9	33 kW	20	5.7	72.4
Raugei *et al.*	2007	South Europe	14	na	20	2.4	72
Jungbluth *et al.*	2007	Switzerland	13.2	na	30	2.9	na
Fthenakis and Alsema	2006	Europe	13.2	na	30	1.5-2.0	36
Alsema *et al.*	2006	Europe	13.2	na	30	1.9	32
Battisti and Corrado	2005	Italy	10.7	1 kW	30	3.3	26.4
Hondo	2005	Japan	10	3 kW	30	Na	53.4
Ito *et al.*	2003	China	12.8	100 MW	30	1.7	12
Alsema and Nieuwlaar	2000	West Europe	13	na	30	3.2	60
Alsema and Nieuwlaar	2000	West Europe	15	na	30	1.7	30
Alsema	2000	Europe	13.2	na	30	3.2	30
Kato *et al.*	1998	Japan	12.8	3 kW	30	2.4	20
Dones and Frischknecht	1998	Switzerland	14	100 kW	30	Na	189
Phylipsen and Alsema	1995	Europe	13	na	25	2.7	na
Tripanagnostopoulos *et al.*	2005	Greece	15	3 kW	20	2.9	104
Seng *et al.*	2008	Malaysia	na	na	na	2.2-3.0	na
Jungbluth	2005	Na	na	na	na	3.0-6.0	39.0-110.0

*na= not available, **two values in the EBPT, for the non-ventilated and ventilated BIPV rooftops feedstock had the greatest environmental impact in each of the studies reviewed. The authors also showed that there is a small difference between mono- and poly-Si PVs that contradicts previous studies that showed a significant gap between these two silicon technologies.

Table 1 shows the energy payback time and GHG emissions of Poly-Si systems, according to the recent literature sources based on 32 papers discussing LCA. Poly-Si technology and the implementation of BIPV were reviewed. The main threads of the literature can be summarized as follows. First, there are only a few, full LCAs "cradle-to-grave" on BIPV systems and many of them do not always incorporate the BOS systems into their LCA. Second, the majority of BIPV as well as ground mounted PVs, are silicone-based PV. The popularity of poly-Si combined with major breakthroughs in efficiency increase, makes them one the best choices for PV applications. The paper by Alaaeddin *et al.* (2019) mentioned a 21.63% module efficiency at poly-Si PV. Finally, of all the BIPV systems, the less popular type is the PVSD. Based on those literature findings this article contributes to environmental analysis of the BIPV and poly-Si PV systems. Further suggestions are made on how to make BIPV applications more sustainable.

Another component for a complete LCA is the inclusion of BOS (balance of system) components into the system assessment. The term BOS encompasses all elements that are required for a PV system except the actual PV panels. Pacca *et al.* (2007) mentioned a 94 MJ/m^2 for array support and cabling. Alsema and Scholten (2005) calculated the inverter's energy consumption to be 1930 MJ/kW with one replacement over the system's lifespan. The GHG emissions over the whole lifetime were also calculated to be 125kg/kW. Another BOS component is the tracking system which also consumes energy for the panel's rotation. Tracking system was estimated to consume 7–13 kWh/kW for double-axis trackers and 4 kWh/kW for horizontal North-South trackers (Perpinan *et al.* 2009).

1.2 Classifying BIPV systems

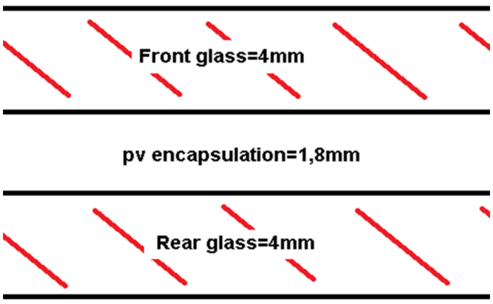
The literature reviewed suggests several ways for classifying BIPV systems, though a universally agreed classification has yet to be reached (Frontini *et al.*2015). According to Shukla *et al.* (2017b) BIPV systems are categorized based on function, materials used and mechanical/electrical characteristics. The categories mentioned comprise: (i) BIPV foil products, (ii) BIPV tile products, (iii) BIPV module products, (iv) BIPV solar cell glazing, and (v) BAPV products. However, Pester and Crick (2013) propose a different categorization of BIPV, mostly based upon usage and on the part of the building where they are integrated, which includes: (i) PV-facades, (ii) PV-windows, (iii) PV-roofs and (iv) PV- sunshades or PVSDs . The last one, promotes the indoor daylight environment, reduce the glaring effect, reduce the heat gain during summer and function as architectural artifact (Zhang *et al.* 2018). According to Sanchez *et al.* (2018), BIPV applications are characterized by a positive aesthetic perception from the public. However, public attitudes differ, as for example the public in Asian countries are still not well acquainted with the integration of PV in the building sector and do not acknowledge it as a stable electricity source (Shukla *et al.* 2018b). Nonetheless, electricity produced from the PV points to a more sustainable building concept. An example of these applications is the zero energy buildings (ZEBs), which include PV systems. These innovative buildings balance their energy usage, in a way that the exported energy equals or exceeds the energy consumed on an annual basis (Yoon *et al.* 2011). Setting aside the building's envelope, various BIPV applications, such as PV wall, contribute to a greater energy efficiency of the building, with minimum environmental footprint (Seyed and Amin 2019).

2. Materials and methods

The BIPV installation assessed here was implemented at Patras Science Park, in Peloponnese, Greece. The installation was part-funded by project "DIDSOLIT_PB" which is abbreviated in, Development and implementation of decentralized solar energy-related innovative technologies for public buildings. This project is part of the EU's ENPI CBC-MED Programme. The location of installation is characterized by high solar irradiance, thus the annual solar energy at horizontal level, ranges from 1450 to 1800 kWh/m^2 (PVGIS). More specifically, the installation includes a car shelter and a skylight with a total installed capacity of 20 kW, grid connected by means of the "net metering" system. Also, electricity generation to the Science Park and CO_2 reduction from the project are continuously monitored. Further technical details of the project include skylights and a car shelter consisting of 22 and 66 panels, respectively. Each panel has a size of 1850x1200 mm (length x width) and thickness of 9.8 mm. All the elements are frameless with each holding a surface of 2.22 m and weighting 44.4 kg. Into the PV encapsulation there is poly-crystalline technology 10th generation as depicted in Fig. 3.

(a)

(b)



(c)

Fig. 3 (a) The skylight before and after the PV installation (Source: authors), (b) The car shelter before and after PV installation (Source: authors) and (c) Project's PV installation pictures and profile (Source: authors)

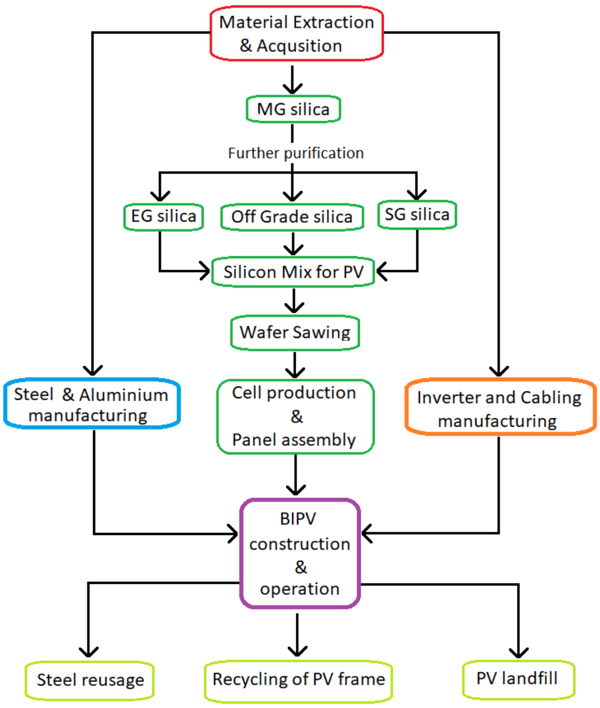


Fig. 2 Silicon PV modules manufacturing line. Source: based on Wong *et al.* (2016)

The primary goal of this study was to quantify and analyze the total environmental aspects of power generation using a BIPV system. Both necessary tools for the actualization of an LCA—a program and an LCI (life cycle inventory)—require high quality of data. Data quality greatly influences the quality of a life cycle assessment. The review on LCA programs by Lehtinen *et al.* (2011), suggested that the *CCaLC 3.3* tool, is a reliable tool supplied on an open-access basis by Manchester University. Many studies also use the database *ecoinvent 3*, which is also used for this study. Due to confidentiality issues, none of the companies participated in the DIDSOLIT-PB project shared data; for the LCI creation. Instead, the LCI data used in our study was drawn from the PV inventories issued by the International Energy Agency (IEA) (Frischknecht *et al.* 2015: pp. 26, 27, 29, 30, 31, 33, 35, 36, 38, 41, 44; Jungbluth *et al.* 2012: 24, 25, 26, 37, 39, 54). Three different LCAs are performed and then combined. The functional unit, for the first one which studies the PV, was assumed to be the weight of one PV module. The second one which estimates the electrical equipment used as a functional unit the nominal power (kW) of the inverter. However, the results are extrapolated for the whole project in a cumulative way. The last LCA includes the structuring support per kg of materials used. These separate LCAs are then combined into a major one, which encompass the environmental impacts of the whole project. Lastly, it can be noted that methodological guidelines of LCA are laid out in the ISO 14040 and ISO 14044 standards (ISO, 2006a, ISO, 2006b) and the impacts were calculated, according with the CML 2001 methodology.

This study is a complete LCA (cradle-to-grave), which means that the system boundary includes all the stages of production from material acquisition to final disposal as it is seen in Fig. 4. Moreover, the Eqs. (1), (2) and (3) would be used, to compare the sustainability of the system with other PV applications.

• Energy payback time (*EPBT*):

$$EPBT = \frac{Total\ primary\ energy\ used\ by\ the\ PV\ throughout\ its\ life\ cycle\ (kWh)}{Annual\ power\ generation\ (kWh/year)} \quad (1)$$

• Energy returned on energy invested (*EROEI*):

$$EROEI = \frac{Life\ time\ (year)}{EPBT\ (year)} \quad (2)$$

• CO_2 emission rate (g CO2/kWh):

$$CO_2 emission\_rate = \frac{Total\ CO2\ emission\ during\ life\ cycle\ (g\ CO2)}{Annual\ power\ generation\ (kWh/year)\ x\ life\ time\ (year)} \quad (3)$$

2.1 PV elements

The whole PV system was supplied by the *Onyx* solar company, Spain. It is believed that *Onyx* sourced quartz sand from Spanish silica mines (Segovia and Guadalajara), as shown in Sanz *et al.* (2008). Eventually, the transport distance from Spanish silicon mining areas to the installation site in Greece was 2,694 km. According to the DIDSOLIT-PB monitoring system, the energy produced between the period of 1st April 2016 and 1st April 2017 reached 27,813.2 kWh. As suggested by the International Energy Agency, the system's aging factor should be 20% of the initial energy produced. Considering a 30-year system lifetime generated energy will reach 777514.1 kWh.

2.2 BOS components

In most cases, a PV electricity system is accompanied by some other parts which include inverter, controller, junction box cabling, array support, battery, etc. Therefore, to calculate the total energy requirement and some other environmental factors the BOS (Balance of System) components study is essential. This includes the following elements.

2.2.1 Metal structure

The metal structure, which supports the car shelter was provided by *Greenox LTD* and. To complement the LCA, the weight of the metal structure was calculated through metal databases, to approximately 7 tons (Macsteel, 2008). The transportation was presumed to be through a road network.

2.2.2 Aluminum structure

The mass of aluminum support for the skylight was estimated according to the data provided from the International Energy Organization which entailed for every square meter of PV panel to use 3.27 kg of aluminum support. The aluminum resources were supposed to be mined from the bauxite quarry at the Parnassos-Gkiona area by a Greek company. In this case also the transportation was estimated to have been through the road network.

Table 2 LCA assumptions

Raw material extraction	•The silica sand was extracted in Spanish mines • The metallic alloys were extracted in Greece
Material Transportation	•Lorry transportation from the mines to the plant
Manufacturing and Assembly	• Due to lack of data the inverter was interpolated by bigger inverters
Product Transportation	• Freight rail from Germany to Greece for the inverter and then lorry transportation to the site • Lorry transportation for the metal and aluminum structure • The PV batch was transported to Greece via a freight ship
Operation	• 30-year lifetime is considered (Frischknecht *et al.* 2015) • 20% degradation over the lifetime(Frischknecht *et al.* 2015) • Total of 88 frameless panels
End-of-life	• PV to landfilling • Aluminum structure recycled • Steel structure remained on site

2.2.3 Electrical systems

The Circulator, which supplements the whole electricity installation, includes two inverters, of 5 and 15kW respectively, junction boxes, cabling, and an online monitoring system. The data that was used for the present study came from Jungbluth *et al.* (2012). Data for the cabling installation came from a 93kW system and were adapted to our 20kW project. Due to lack of data for the inverter, data were extrapolated from a system with 2.5 kW inverter and multiplied to match a 5 and 15 kW inverting system.

3. Results of the LC impact assessment

The Life cycle impact metrics defined in equations 1, 2 and 3 (Tripathy *et al.* 2016) comprise energy payback time, energy returned on energy invested and life cycle emissions. The results for our BIPV system were 7.94 years for EPBT, 3.78 for EROEI and 6.46 g CO_2 per kWh for carbon cycle emissions. Our figures far exceed the average values obtained from the literature, which (as shown in Table 1) were 2.83±1.12 years for EPBT (n.b. omitting Stoppato's 2008 results as outliers), 9.72 years for EROEI and 92.42 ± 40.59 g CO_2 per kWh carbon cycle emissions. This difference was due to the unusually massive steel pillars installed in the BIPV system examined here (see further discussion in section 4).

Furthermore, environmental impact can be assessed separately for the PV systems and for the BOS components. A distinction is also possible for each production stage (acquiring raw materials, production, and transport) and for the materials used (reinforced steel, copper etc.) In Table 3, every environmental treadmill caused from the project and its units of measurement is shown. In

Table 3 Life cycle environmental impacts caused by PV systems and BOS components

Environmental Aspect	LCA on PV	LCA on BOS	Total
Carbon footprint (kg CO_2)	36200	14000	50200
Acidification potential (kg SO_2)	190	60.1	250
Eutrophication potential (kg phosphate eq.)	47.5	42.6	90.1
Ozone layer depletion potential (kg R11 eq.)	0.00401	0.000577	0.00459
Photochemical smog potential summary (kg ethene eq.)	0.22	7.82	8.04
Human toxicity potential (kg dichlorobenzene eq.)	3870000	27800	3900000
Cumulative energy demand (kWh)	159000	61800	221000

Table 4 Life cycle environmental impacts of the PV system and its production stages

Environmental aspect for the PV system	Raw materials	Production	Transport	Total
Carbon footprint (kg CO_2)	21800	14100	277	36200
Acidification potential (kg SO_2)	142	45	3.05	190
Eutrophication potential (kg phosphate eq.)	37.9	9.16	0.529	47.6
Ozone layer depletion potential (kg R11 eq.)	0.00252	0.00146	0.000034	0.00401
Photochemical smog potential summary (kg ethene eq.)	5.94	2.18	0.097	8.22
Human toxicity potential (kg dichlorobenzene eq.)	20900	3850000	129	3870000
Cumulative energy demand (kWh)	96700	61500	1208	159000

Table 5 Life cycle environmental impacts of the BOS components and the production stages

Environmental aspect for the PV system	Raw materials	Production	Transport	Total
Carbon footprint (kg CO_2)	13600	243	193	14000
Acidification potential (kg SO_2)	59.2	0.178	0.708	60.1
Eutrophication potential (kg phosphate eq.)	42	0.472	0.19	427
Ozone layer depletion potential (kg R11 eq.)	0.000641	5.16E-06	0.0000306	0.000677
Photochemical smog potential summary (kg ethene eq.)	7.78	0.00797	0.028	7.82
Human toxicity potential (kg dichlorobenzene eq.)	27300	457	53.9	27800
Cumulative energy demand (kWh)	60300	545	911	61800

Tables 4 and 5, the environmental impact over the production stages for the PV systems and for the BOS components respectively are presented.

The results of our LCA indicated an EPBT of 7.94 years, an EROEI of 3.78 and GHG of 6.46 gCO2 per kWh, respectively. On the other hand, Table 1 showed 2.83±1.12 years, 9.72 years and

92.42±40.59, respectively. It can be suggested that, in our LCA, the increased EPBT without much emissions was caused from the massive 7-ton steel construction (BOS), which required large amounts of energy, increasing the time for the PV system to pay back this energy. It can be claimed that the steel structure is making the project less environmentally friendly. Improvements like a wooden structure could have made the project architecture interesting, more aesthetical, and sustainable. However, the steel structure was calculated to have only 30 years of lifetime, which is unrealistic, because if a new PV is installed after the 30-year PV lifetime, the project's impact will be significantly lower. Finally, the high EROEI proves that PV applications are proved to be a sustainable energy source which can provide electricity for more than 30 years even with a low efficiency.

4. Discussion

The article considered current assumptions and findings concerning the sustainability of BIPV systems (Frischknecht *et al.* 2015; Jungbluth *et al.* 2012). Energy consumption from storage, construction and dismantling (at the end of life) were not considered significant parameters, due to the fact that supplier companies, were preempted from storing and secondly, because construction was quick, with five workers and an advanced suction cupping tool, taking only three days for the project to complete.

New research is required to account for the environmental cost of disposal and recycling. Landfill disposal was considered in this study following the available studies (Frischknecht *et al.* 2015; Jungbluth *et al.* 2012). Nonetheless, recycling is often considered of little significance in terms of contributing to environmental problems in the whole life cycle compared to production (Bogacka *et al.* 2017). However, Vellini *et al.* (2017) disagree with the previous assessment, suggesting that PV recycling has major positive impacts on the environment, by significantly decreasing terrestrial ecotoxicity potential by approximately 73%. In the years to come PV recycling will pose a major challenge. As presented in Peeters *et al.* (2017) 22,000 tons per year will have to be recycled in Flanders Belgium alone. In Tables 6 and 7, the environmental impact of most polluting materials used for the PV system and for BOS components, are presented, separately. In that way the most polluting materials can be identified for potential replacement or environmental improvement thus leading to upgrades in the overall profile of the BOS or PV components.

To identify potential improvements in each cumulative environmental impact for the top 5 component materials we summarized their total environmental footprint in the last columns of Tables 6 and 7, which show first, the total and second, the percentage values of the summary for each environmental problem after division with the last column of Table 3. Furthermore, as it can be seen on Tables 6 and 7, there are some major contributors which play a significant role in sustainability reduction for each environmental aspect of both BOS and PV. The key contributors for PV are the reinforced glass fiber, uncoated flat glass, low iron solar glass, aluminum alloy. For the BOS it is the aluminum and the reinforced steel components. Specified and targeted improvements can be made, if the major elements that have the worst environmental profile can be identified.

Lastly, Ferroni and Hopkirk (2016) mentioned that PV applications in Switzerland and Germany EROEI are significantly below 1, supporting that current PV technologies have a non-sustainable profile associated with net energy loss. In the DIDSOLIT-PB application it was shown

Table 6 Top five materials of the PV system participating in each environmental problem

Environmental aspect for each PV material (top 5)	Materials	Values*	Total	Percentage (%)
Carbon footprint (kg CO_2)	Glass fiber reinforced	5001.3	17400.85	34.7
	Aluminum alloy	2428.2		
	Flat glass uncoated	3802.25		
	Solar glass low iron	4205.6		
	Tempering flat glass	1963.5		
Acidification potential (kg SO_2)	Glass fiber reinforced	18.7	107.53	43.0
	Aluminum alloy	7.86		
	Flat glass uncoated	33.12		
	Solar glass low iron	39.32		
	Hydrogen fluoride	8.53		
Eutrophication potential (kg phosphate eq.)	Glass fiber reinforced	4.57	22.1	24.5
	Flat glass uncoated	4.13		
	Solar glass low iron	5.16		
	Metallization paste	4.46		
	Copper, at regional	3.78		
Ozone layer depletion potential (kg R11eq.)	Glass fiber reinforced	0.00042	0.00177	38.6
	Aluminum alloy	0.0001		
	Flat glass uncoated	0.00035		
	Solar glass low iron	0.0004		
	Silicone product	0.0005		
Photochemical smog potential (kg ethane eq.)	Glass fiber reinforced	0.78	4.192	26.1
	Aluminum alloy	0.52		
	Flat glass uncoated	1.121		
	Solar glass low iron	1.391		
	Hydrogen fluoride	0.38		
Human toxicity potential (kg dichlorobenzene eq.)	Aluminum alloy	5635.2	13611.6	0.3
	Solar glass low iron	1368.9		
	Metallization paste	2576.3		
	Copper at regional	2904.9		
	Wire drawing Copper	1126.3		
Cumulative energy demand (kWh)	Glass fiber reinforced	23700	6.61E+04	29.9
	Aluminum alloy	8360		
	Flat glass uncoated	13800		
	Solar glass low iron	15900		
	Ethyl vinyl acetate	4369		

*values were calculated from the authors using *CCaLC2* software

Table 7 Top five materials of the BOS components participating in each environmental problem

Environmental aspect for each BOS material (top 5)	Materials	Values*	Total	Percentage (%)
Carbon footprint (kg CO_2)	Reinforcing steel	10000	1.23E+04	24.4
	Aluminum	1738		
	Integrated circuit	225		
	Extrusion aluminum	171		
	Inductor ring core	118		

Table 7 Top five materials of the BOS components participating in each environmental problem

Environmental aspect for each BOS material (top 5)	Materials	Values*	Total	Percentage (%)
Acidification potential (kg SO_2)	Reinforcing steel Aluminum Integrated circuit Copper at regional storage Capacitor film	35.7 8.13 1.11 8.37 0.938	5.42E+01	21.7
Eutrophication potential (kg phosphate eq.)	Reinforcing steel Aluminum Integrated circuit Copper at regional storage Capacitor film	2.19 2.87 3.07 9.89 0.768	1.88E+01	20.9
Ozone layer depletion potential (kg R11eq.)	Reinforcing steel Aluminum Integrated circuit Capacitor film Capacitor, tantalum	0.00042 0.0001 0.00035 0.000088 0.000015	7.27E-04	15.8
Photochemical smog potential (kg ethane eq.)	Reinforcing steel Aluminum Inductor ring core Copper at regional storage Capacitor film	5.69 0.685 0.258 0.313 0.268	7.21E+00	45.0
Human toxicity potential (kg dichlorobenzene eq.)	Reinforcing steel Aluminum Integrated circuit Copper at regional storage Steel low alloy	6284 8504 1061 8709 603	2.52E+04	0.6
Cumulative energy demand (kWh)	Reinforcing steel Aluminum Extrusion aluminum Capacitor film IC, logic type at plant	45000 7789 940 896 1011	5.56E+04	25.2

*values were calculated from the authors using *CCaLC2* software

that the EROEI is almost four. This optimistic calculation was made firstly because of the high sunshine occurring in Greece and secondly because of labor and capital requirements, which were not considered in this study. One more factor that was not thoroughly studied is the climate/weather variation, which can cause variation at the energy production (Choi *et al.* 2016). Lastly, it is reminded that this BIPV application is located in the Science park of the University of Patras. The science park receives lots of visitors which can be positively influenced by this BIPV application. Evidence of this behavior is seen in Sicily, Italy, where the development of innovative energy technologies and especially renewable ones, resulted in the development of a new tourism type (Michalena and Tripanagnostopoulos 2010).

5. Conclusions

The article presented a detailed LCA for a car shelter and skylight. The main indices comparing sustainability indicators are EPBT and GHG emissions. Our project had an EPBT that was almost threefold the average mean. This was observed because of the massive BOS components used in this project which increased the energy needed for assembly without necessarily increasing the project's emissions. On the other hand, CO_2 levels were significantly lower than the literature average.

Special consideration needs to be taken on the sustainability of materials used, to pinpoint environmentally "weak" elements of the BIPV. The novelty of this project is that there is a clear identification of these materials, which if addressed, leads to considerably increased environmental performance of the system. Notably, for the PV system, materials like aluminum alloy, glass reinforced, or uncoated and solar glass require further attention in finding ways to improve the environmental footprint of production. Likewise, for the BOS components reinforcing steel, aluminum, and integrated circuit additional study is required.

Percentage contributions to environmental impact (Tables 6 and 7, last column) were added to estimate the total polluting contribution that can be avoided if treated. This means that the most polluting agents are identified and if fully treated, strong pollution reduction and sustainability gains can be achieved. The percentages of pollution reduction are as follows:

- Carbon footprint (kg CO_2): 59.09%
- Acidification potential (kg SO_2): 64.69%
- Eutrophication potential (kg phosphate eq.): 45.38%
- Ozone layer depletion potential (kg R11 eq.): 54.44%
- Photochemical smog potential summary (kg ethene eq.): 71.11%
- Human toxicity potential (kg dichlorobenzene eq.): 0.99%
- Cumulative energy demand (kWh): 55.15%

These percentages strongly support existing evidence concerning the five most pollutant materials used for the PV production. Finding ways to make these materials more sustainable will help make PV technology greener. The only exception is with the potential for improvement for human toxicity, which at almost 1% potential indicates that the major gains can be made elsewhere in the production process. The proliferation of different PV technologies will lower the toxicity impact, but surely more investigation is required to this end.

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References

Alaaeddin, M.H., Sapuan, S.M., Zuhri, M.M., Zainudin, E.S. and Faris-Oqla, M.L. (2019), "Photovoltaic applications: Status and manufacturing prospects", *Renew. Sust. Energy Rev.*, **102**, 318-332. https://doi.org/10.1016/j.rser.2018.12.026.

Alsema E.A. (2000), "Energypay-back time and CO2 emissions of PV systems", *Progress Photovoltaics*

Res. *Appl*., **8**(1), 17-25. https://doi.org/10.1002/(SICI)1099-159X(200001/02)8:1<17::AID-PIP295>3.0.CO;2-C.

Alsema, E.A. and Nieuwlaar, E. (2000), “Energy viability of photovoltaic systems”, *Energy Policy*, **28**(14), pp. 999-1010. https://doi.org/10.1016/S0301-4215(00)00087-2.

Alsema, E.A. and Wild-Scholten, M.J. (2005), “Environmental impacts of crystalline silicon photovoltaic module production”, *Proceedings of the Materials Research Society Fall Meeting*, Boston, Massachusetts, U.S.A., November-December.

Alsema, E.A., Wild-Scholten, M.J. and Fthenakis, V.M. (2006), “Environmental impacts of PV electricity generation-acritical comparison of energy supply options”, *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, September.

Battisti, R. and Corrad, A. (2005), “Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology”, *Energy*, **30**(7), 952-967. https://doi.org/10.1016/j.energy.2004.07.011.

Bogacka, M., Pikon, K. and Landrat, M. (2017), “Environmental impact of PV cell waste scenario”, *Waste Manage*., **70**, 198-203. https://doi.org/10.1016/j.wasman.2017.09.007.

Carnevale A.E., Lombardi L. and Zanchi L. (2016) “Wind and solar energy: a comparison of costs and environmental impacts”, *Adv. Energy Res*., **4**(2), 121-146. https://doi.org/10.12989/eri.2016.4.2.121.

Choi, W., Warren, D.R. and Pate, B.M. (2016) “An experimental performance analysis of a cold region stationary photovoltaic”, *Adv. Energy Res*., **4**(1), 1-28. http://doi.org/10.12989/eri.2016.4.1.001.

Desideri, U., Proietti, S., Zepparelli F., Sdringola, P. and Bini, S. (2012), “Life cycle assessment of a ground-mounted1778kW photovoltaic plant and comparison with tra-ditional energy production systems”, *Appl. Energy*, **97**, 930-943. https://doi.org/10.1016/j.apenergy.2012.01.055.

DIDSOLIT_PB Project. (2017), *Development & Implementation of Decentralised Solar Energy-Related Innovative Technologies for Public Buildings in the Mediterranean Basin Countries*, http://monitoritzacio.dyndns.org:1234/html5/index.html.

Dones, R. and Frischknecht, R. (1998), “Life-cycle assessment of photovoltaic systems: Results of Swiss studies on energy chains”, *Progress Photovoltaics Res. Appl*., **6**(2), 117-125. https://doi.org/10.1002/(SICI)1099-159X(199803/04)6:2<117::AID-PIP209>3.0.CO;2-M.

EIA (2016), *International Energy Outlook 2016*, U.S. Department of Energy, Washington, D.C., U.S.A.

European Commission. (2011), *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*, Brussels, Belgium.

Ferroni, F. and Hopkirk, R.J. (2016), “Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation”, *Energy Policy*, **94**, 336-344. https://doi.org/10.1016/j.enpol.2016.03.034.

Fiandra, V., Sannino, L., Andreozzi, C. and Graditi, G. (2019), “End-of-life of silicon PV panels: A sustainable materials recovery process”, *Waste Manage*., **84**, 91-101. https://doi.org/10.1016/j.wasman.2018.11.035.

Frischknecht, P., Itten, R., Sinha, P., de Wild-Scholten, M., Zhang, J. and Fthenakis, V. (2015), “Life cycle inventories and life cycle assessments of photovoltaic systems”, Report T12-04:2015, International Energy Agency (IEA) PVPS Task 12.

Frischknecht, P., Itten, R., Sinha, P., de Wild-Scholten, M., Zhang, J. and Fthenakis, V. (2015), “Life cycle inventories and life cycle assessments of photovoltaic systems”, Report T12-04:2015, International Energy Agency (IEA) PVPS Task 12.

Frontini, F., Bonomo, P. and Chatzipanagi, A. (2015), “BIPV product overview for solar facades and roofs”, SUPSI Report.

Fthenakis V.M., Alsema E. (2006), “Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004 –early 2005 status”, *Prog. Photovoltaics*, **14**(3), 275-280. https://doi.org/10.1002/pip.706.

Fthenakis, V.M.,Kim H.C.,Alsema E.A. (2008), “Emissions from photovoltaic life cycles”, *Environ. Sci. Technol*., **42**(6), 2168-2174. https://doi.org/10.1021/es071763q.

Gløckner, R., Odden, J.O., Halvorsen, G., Tronstad, R. and Wild-Scholten, M.J. (2008), “Environmental lifecycle assessment of the Elkem solar metallurgical process route to solar grade silicon with focus on energy consumption and greenhouse gas emissions", *Proceedings of the Silicon for the Chemical and Solar Industry IX*, Oslo, Norway, June.

Granata, G., Pagnanellia, F., Moscardini, E., Havlik, T. and Toro, L. (2014), "Recycling of photovoltaic panels by physical operations", *Solar Energy Mater. Solar Cells*, **123**, 239-248. https://doi.org/10.1016/j.solmat.2014.01.012.

Hondo, H. (2005), "Life cycle GHG emission analysis of power generation systems: Japanese case", *Energy*, **30**(11-12), 2042-2056. https://doi.org/10.1016/j.energy.2004.07.020.

ISO 14040 (2006a), Environmental Management - Life Cycle Assessment – Principlesand Framework, International Standards Organisation, Geneva, Switzerland.

ISO 14044 (2006b), Environmental Management - Life Cycle Assessment - Requirements and Guidelines, International Standards Organization, Geneva, Switzerland.

Ito, M., Kato, K., Komoto, K., Kichimi, T. and Kurokawa, K. (2007), "Comparative study on cost and life-cycle analysis for 100MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules", *Prog. Photovoltaics*, **16**(1), 17-30. https://doi.org/10.1002/pip.770.

Ito, M., Kato, K., Komoto, K., Kichimi, T., Sugihara, H. and Kurokawa, K. (2003), "An analysis of variation of very large-scale PV (VLS-PV) systems in the world deserts", *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, Osaka, Japan, May.

Ito, M., Komoto, K. and Kurokawa, K. (2010), "Life-cycle analyses of very-large scale PV systems using six types of PV modules", *Current Appl. Phys.*, **10**(2), 271-273. https://doi.org/10.1016/j.cap.2009.11.028

Jungbluth, N. (2005), "Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database", *Prog. Photovoltaics*, **13**(5), 429-446. https://doi.org/10.1002/pip.614.

Jungbluth, N., Dones, R. and Frischknecht, R. (2007), "Life cycle assessment of photo-voltaics; update of the ecoinvent database", *Proceedings of the 14th SETAC LCA Case Studies Symposium*, Goteborg, Sweden, December.

Jungbluth, N., Stucki, M., Flury, K., Frischknecht, R. and Büsser, S. (2012), Life Cycle Inventories of Photovoltaics, *ESU-services Ltd. Uster*. http://esu-services.ch/fileadmin/download/publicLCI/jungbluth-2012-LCI-Photovoltaics.pdf.

Kato, K., Murata, A. and Sakuta, K. (1998), "Energy pay-back time and life-cycle CO2 emission of residential PV power system with silicon PV module", *Prog. Photovoltaics*, **6**(2), 105-115. https://doi.org/10.1002/(SICI)1099-159X(199803/04)6:2<105::AID-PIP212>3.0.CO;2-C.

Kim, B., Lee, J., Kim, K. and Hur, T. (2014), "Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea", *Sol. Energy*, **99**, 100-114. https://doi.org/10.1016/j.solener.2013.10.038.

Kumar V., Teja R.V., Singh M. and Mishra S. (2019), "PV based off-grid charging station for electric vehicle", *Proceedings of the IFAC Workshop on Control of Smart Grid and Renewable Energy Systems CSGRES 2019*, Jeju, Korea, June.

Lehtinen, H., Saarentaus, A., Rouhiainen, J., Pitts, M. and Azapagic, A. (2011), "A review of LCA methods and tools and their suitability for SMEs", BIO-CHEM Project Report, Europe Innova.

Macsteel (2008), Database of Structual Steel Sections, https://www.macsteel.co.za/files/saisc_structural_steel_section_properties.xls.

Mansoor A., Sultana B., Shafigue S. and Zaman K. (2019), "The water-energy-food resources and environment: Evidence from selected SAARC", *Adv. Energy Res.*, **6**(1), 1-15. http://doi.org/10.12989/eri.2019.6.1.001.

Mesaritis, G., Symeou, E., Delimitis, Oikonomidis, S., Jaegle, M., Tarantik, K., Nicolaou, C. and Kyratsi, T. (2019), "Recycling Si-kerf from photovoltaics: A very promising route to thermoelectrics", *J. Alloy. Compd.*, **775**, 1036-1043. https://doi.org/10.1016/j.jallcom.2018.10.050.

Michalena E. and Tripanagnostopoulos Y. (2010), "Contribution of the solar energy in the sustainable tourism development of the Mediterranean islands", *Renew. Energ.*, **35**(3), 667-673. https://doi.org/10.1016/j.renene.2009.08.016.

Nishimura, A., Hayashi, Y., Tanaka, K., Hirota, M., Kato, S. and Ito, M. (2010), "Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system", *Appl.*

Energy, **87**(9), 2797-2807. https://doi.org/10.1016/j.apenergy.2009.08.011.

NREL (2012), Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics, https://www.nrel.gov/docs/fy13osti/56487.pdf.

Pacca S., Sivaraman, D. and Keoleian G. (2006), "Life cycle assessment of the 33 kW photovoltaic system on the Dana Building at the University of Michigan", A report of the Center for Sustainable Systems: Report No. CSS05-09, University of Michigan, Michigan, U.S.A.

Pacca, S., Sivaraman, D. and Keoleian, G. (2007), "Parameters affecting the life cycle performance of PV technologies and systems", *Energy Policy*, **35**(6), 3316-3326. https://doi.org/10.1016/j.enpol.2006.10.003.

Padoan, F., Altimari, P. and Pagnanelli, F. (2019), "Recycling of end of life photovoltaic panels: A chemical prospective on process development", *Sol. Energ.*, **177**, 746-761. https://doi.org/10.1016/j.solener.2018.12.003.

Peeters, J., Altamirano, D., Dewulf, W. and Duflou, R. (2017), "Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders", *Resour. Conserv. Recy.*, **120**, 14-26. https://doi.org/10.1016/j.resconrec.2017.01.001.

Peng, J., Lu, L. and Yang, H. (2013), "Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems", *Renew. Sust. Energ. Rev.*, **19**(3), 255-274. https://doi.org/10.1016/j.rser.2012.11.035.

Perez-Lombard, J., Ortiz, J. and Pout, C. (2008), "A review on buildings energy consumption information", *Energ. Buildings*, **40**(3), 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007.

Perpinan, O., Lorenzo, E., Castro, M. and Eyras, R. (2009), "Energy payback time of grid connected PV systems: Comparison between tracking and fixed systems", *Prog. Photovoltaics*, **17**(2), 137-147. https://doi.org/10.1002/pip.871.

Pester, S. and Crick, F. (2013), *Performance of Photovoltaic Systems on Non-domestic Buildings*, IHS BRE Press, U.K.

Phylipsen, G.M. and Alsema, E.A. (1995), "Environmental life-cycle assessment of multi-crystalline silicon solar cell modules", Report no. 95057, Department of Science, Technology and Society, Utrecht University, Utrecht, The Netherlands.

Raugei, M., Bargigli, S. nad Ulgiati, S. (2007), "Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si", *Energy*, **32**(8), 1310-1318. https://doi.org/10.1016/j.energy.2006.10.003.

Ritzen, M.J., Vroon, Z., Rovers, R., Lupíšek, A. and Geurts, C. (2017), "Environmental impact comparison of a ventilated and a non-ventilated building-integrated photovoltaic rooftop design in the Netherlands: Electricity output, energy payback time, and land claim", *Sol. Energy*, **155**, 304-313. https://doi.org/10.1016/j.solener.2017.06.041.

Sánchez-Pantoja, N., Vidal, R. and Pastor, M.C. (2018), "Aesthetic perception of photovoltaic integration within new proposals for ecological architecture", *Sustain. Cities Soc.*, **39**, 203-214. https://doi.org/10.1016/j.scs.2018.02.027.

Sanz, M. A., Martín-Duque, J.F., Martín-Moreno, C., Lucía, A., Nicolau, J.M., Pedraza, J., Sánchez, L., Ruiz, R. and García, A. (2008), Silica sand slope gullying and mining in Central Spain: erosion processes and geomorphic reclamation of contour mining, Geo-Environment and Landscape Evolution III, https://www.witpress.com/Secure/elibrary/papers/GEO08/GEO08001FU1.pdf.

Sardi J., Mithulananthan N. and Hung D.Q. (2017), "Strategic allocation of community energy storage in a residential system with rooftop PV units", *Appl. Energ.*, **206**(15), 159-171. https://doi.org/10.1016/j.apenergy.2017.08.186.

Seng, L.Y., Lalchand, G., Sow-Lin, G.M. (2008), "Economical, environmental and technical analysis of building integrated photovoltaic systems in Malaysia", *Energ. Policy*, **36**(6), 2130-2142. https://doi.org/10.1016/j.enpol.2008.02.016.

Sharif, S. and Hammad. A. (2019), "Simulation-based multi-objective optimization of institutional building renovation considering energy consumption life-cycle cost and life-cycle assessment", *J. Build. Eng.*, **21,** 429-445. https://doi.org/10.1016/j.jobe.2018.11.006.

Sherwani, A.F. and Usmani, J.A. (2010), "Life cycle assessment of solar PV based electricity generation

systems: A review", *Renew. Sust. Energ. Rev.*, **14**(1), 540-544. https://doi.org/10.1016/j.rser.2009.08.003.
Shukla, A.K., Sudhakar K. and Baredar, P. (2017b), "Recent advancement in BIPV product technologies: A review", *Energ. Buildings*, **140**, 188-195. https://doi.org/10.1016/j.enbuild.2017.02.015.
Shukla, A.K., Sudhakar K., Baredar, P. and Mamat, R. (2017a), "BIPV in Southeast Asian countries – opportunities and challenges", *Renew. Energy Focus*, **21**, 25-32. https://doi.org/10.1016/j.ref.2017.07.001.
Shukla, A.K., Sudhakar K., Baredar, P. and Mamat, R. (2018a), "Solar PV and BIPV system: Barrier, challenges and policy recommendation in India", *Renew. Sust. Energ. Rev.*, **82**(3), 3314-3322. https://doi.org/10.1016/j.rser.2017.10.013.
Shukla, A.K., Sudhakar K., Baredar, P. and Mamat, R. (2018b), "BIPV based sustainable building in South Asian countries", *Sol. Energy*, **170**, 1162-1170. https://doi.org/10.1016/j.solener.2018.06.026.
Stoppato, A. (2008), "Life cycle assessment of photovoltaic electricity generation", *Energy*, **33**(2), 224-232. https://doi.org/10.1016/j.energy.2007.11.012.
The Royal Academy of Engineering (2010), Engineering a low carbon built environment: The discipline of Building Engineering Physics, http://www.raeng.org.uk/publications/reports/engineering-a-low-carbon-built-environment.
Tripanagnostopoulos, Y., Souliotis, M., Battisti, R. and Corrado, A. (2005), "Energy, cost and LCA results of PV and hybrid PV/T solar systems", *Prog. Photovoltaics*, **13**(3), 235-250. https://doi.org/10.1002/pip.590.
Tripathy, M., Sadhu, P.K. and Panda, S.K. (2016), "A critical review on building integrated photovoltaic products", *Renew. Sust. Energ. Rev.*, **61**(3), 451-465. https://doi.org/10.1016/j.rser.2016.04.008.
Tupule, J.P., Marano, V., Yurkovich, S. and Rizzoni, G. (2013), "Economic and environmental impacts of a PV powered workplace parking garage charging station", *Appl. Energ.*, **108**, 323-332. https://doi.org/10.1016/j.apenergy.2013.02.068.
Vellini, M., Gambini, M. and Prattella, V. (2017) "Environmental impacts of pv technology throughout the life cycle: Importance of the end-of-life management for si-panels and cdte-panels", *Energy*, **138**, 1099-1111. https://doi.org/10.1016/j.energy.2017.07.031.
Vilches, A., Garcia-Martinez, A. and Sanchez-Montañes, B. (2017), "Life cycle assessment (LCA) of building refurbishment: A literature review", *Energ. Buildings*, **135**, 286-301. https://doi.org/10.1016/j.enbuild.2016.11.042.
Wang, W., Liu, Y., Wu, X., Xu, Y., Yu, W., Zhao, C. and Zhong, Y. (2016), "Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai", *Energ. Buildings*, **130**, 98-106. https://doi.org/10.1016/j.enbuild.2016.07.066.
Wild-Scholten, M.J. (2009) "Energy payback times of PV modules and systems", *Proceedings of the Workshop Photovoltaik-Modultechnik*, Koeln, Germany, November.
Wong, J.H., Royapoor, M. and Chan, C.W. (2016), "Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems", *Renew. Sust. Energ. Rev.*, **58**, 608-618. https://doi.org/10.1016/j.rser.2015.12.241.
Yoon, J.H., Song, J., Lee, S.J. (2011), "Practical application of building integrated photovoltaic (BIPV) systems using transparent amorphous silicon thin-film module", *Sol. Energy*, **85**(5), 723-733. https://doi.org/10.1016/j.solener.2010.12.026.
Yue, D., You. F. and Darling, B. (2014), "Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental", *Sol. Energy*, **105**, 669-678. https://doi.org/10.1016/j.solener.2014.04.008.
Zhai, P. and William, E.D. (2010), "Dynamic hybrid life cycle assessment of energy and carbon of multicrystalline silicon photovoltaic systems", *Environ. Sci. Technol.*, **44**(20), 7950-7955. https://doi.org/10.1021/es1026695.
Zhang, X., Lau, S.K., Lau, S.S. and Zhao, Y. (2018), "Photovoltaic integrated shading devices (PVSDs): A review", *Sol. Energy*, **170**, 947-968. https://doi.org/10.1016/j.solener.2018.05.067.