Dielectric-based 3D building-integrated concentrating photovoltaic modules: an environmental life-cycle assessment

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ABSTRACT

The environmental profile of a dielectric-based 3D Building-Integrated Concentrating Photovoltaic (BICPV) device is investigated. Several scenarios and life-cycle impact assessment methods are adopted, including the newly-developed method ReCiPe. Multiple environmental indicators are evaluated for different cities: Barcelona, Seville, Paris, Marseille, London and Aberdeen. The results from the material manufacturing phase demonstrate that the PV cells and the concentrator are the components with the highest contribution to the total impact of the BICPV, based on ReCiPe, Eco-indicator 99, USEtox, CED (cumulative energy demand), GWP (global warming potential) according to different time horizons (20a, 100a, 500a) and Ecological footprint. Among the studied cities, Barcelona, Marseille and Seville present the lowest GWP and CED: less than 142 g $CO_{2.eq}$/kWh and less than 2.9 MJ_{prim}/kWh, based on all the studied scenarios. Moreover, by considering 30-years lifespan, Barcelona, Marseille and Seville show 0.0107-0.0111 ReCiPe Pts/kWh while London, Paris and Aberdeen present 0.0161-0.0173 ReCiPe Pts/kWh. Results about greenhouse-gas-, energy-, ReCiPe-payback times and energy-return-on-the-investment are also presented and critically discussed. In addition, comparisons with the literature and issues for the improvement of the environmental profile of the proposed system are included.

Keywords: Life Cycle Assessment (LCA); Concentrating Photovoltaics (CPVs); 3D Cross Compound Parabolic Concentrator (CCPC); Building-Integrated CPV (BICPV); Global Warming Potential (GWP); Cumulative Energy Demand (CED); ReCiPe; Eco-indicator 99 (EI99); Ecological footprint; USEtox

LIST OF SYMBOLS AND ACRONYMS

a-Si	amorphous silicon
BI	Building integrated
BICPV	Building integrated concentrating photovoltaic
BIPV	Building integrated photovoltaic
BOS	Balance of system
CCPC	Cross compound parabolic concentrator
CdTe	Cadmium telluride
CED	Cumulative energy demand
CIGS	Copper indium gallium diselenide
CML-IA	CML-IA method

$CO_{2.eq}$	$CO_{2.equivalent}$
CPC	Compound parabolic concentrator
CPV	Concentrating photovoltaic
CPVT	Concentrating photovoltaic/thermal
CR	Concentration ratio
CTU_e	Comparative toxic unit for ecosystems
CTU_h	Comparative toxic unit for humans
DC	Direct current
EF	Ecological footprint
EI99	Eco-indicator 99 method
EPBT	Energy payback time
EPS 2000	EPS 2000 method
EROI	Energy return on investment
GHG PBT	Greenhouse gas payback time
GHG	Greenhouse gas
GWP 100a	Global warming potential with a time horizon of 100 years
GWP 20a	Global warming potential with a time horizon of 20 years
GWP 500a	Global warming potential with a time horizon of 500 years
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
M.R.	Material replacement
MJ_{prim}	$MJ_{primary}$
nc-Si	Nanocrystalline silicon
PBT	Payback time
Pts	Points
PV	Photovoltaic
ReCiPe PBT	ReCiPe payback time
ReCiPe	ReCiPe method
Si	Silicon
USEtox	USEtox method

1. INTRODUCTION

The concept of Building-Integrated Photovoltaic (BIPV) refers to PV modules which can be integrated into the building architecture and replace an existing building element (e.g. façade, roof, skylight, etc.). BIPV provide material replacement (e.g. replacement of the materials of a wall: an advantage that is not provided by the traditional building-added PV modules which do not replace a building element) and at the same time generate electricity [1].

According to the status report SUPSI-SEAC about BIPV (year of the study: 2015) [1], the European BIPV market is supported by about 200 commercially available products, of which 108 are listed in the report [1]. The products are well-distributed over 3 application areas and 13 product categories and the most abundantly populated product categories are the «full roof solution» and the «solar glazing». Moreover, it was mentioned that BIPV façades are very promising financially since they were priced very similar to the conventional façade materials. In addition, it was highlighted that the dominant PV technology in BIPV today (year of the study: 2015) is crystalline silicon and that multi-functionality, prefabrication, standardization, mass customization, aesthetic and cost-effectiveness are the main pillars on which BIPV development is evolving [1].

Within the field of BIPV applications, Concentrating Photovoltaic (CPV) technology can be adopted. CPVs use an optical concentrator (e.g. Fresnel lens or reflector) in order to concentrate the incoming sunlight onto small-sized PV cells. This means that less PV-cell material is used per kWh of electricity generated. CPVs of low Concentration Ratio (CR) offer multiple benefits for BI applications and they are known as BICPV systems [2]. BICPV configurations can be integrated for example into the façade of a building or into the roof (flat or sloped) producing in each case a different visual impact. Depending on the device type, the system may be integrated in such a way that it can be unseen which plays a role in the architectural aesthetic. Other advantages of the BICPVs (which are provided in general by the CPV systems) are related with the higher electrical conversion efficiency in the PV cells and lower surface requirements for equivalent electricity production (in comparison to PV modules without concentration) [2].

In terms of the CPV market, the global CPV market is expected to undergo a major growth spurt in the next years, with its cumulative installed capacity forecast to jump from 357.9 MW in 2014 to 1,043.96 MW by 2020 [3]. This increasing interest for CPV includes also an increasing interest for BICPV. Several BICPV systems have been studied in the last few years using both reflective- and refractive-based optical concentrators. In the following paragraphs literature studies about several BICPV configurations are presented, showing the benefits of the BICPV technology.

Baig et al. [4, 5] conducted a performance analysis of a dielectric based 3D BICPV system with a geometric CR of 3.6×. Moreover, a linear asymmetric Compound Parabolic Concentrator (CPC) with a geometrical CR of 2.8× was investigated [6]. Furthermore, a BICPV with 6× geometrical CR was studied [7], including modelling and indoor experiments (by means of a solar simulator) [7]. In addition, Zacharopoulos et al. [8] presented a detailed optical analysis of two non-imaging, dielectric, linear concentrators for PVs for building-façade applications. Mallick et al. [9] conducted an experimental comparison of non-concentrating and asymmetric CPC façade-integrated PVs. Sarmah and Mallick [10] designed and constructed a CPV module with low-concentrating dielectric CPC for outdoor characterisation (CR 2.8×).

From the above mentioned studies it can be seen that BICPV systems present several interesting characteristics (utilization of less PV cell material, replacement of the PV cell material by a concentrator, increase of PV output due to sunlight concentration, etc.) which are not provided by the PVs without concentration. Thereby, studies about BICPV environmental profile, by means of Life Cycle Assessment (LCA), can offer useful information. Several LCA studies on PV systems without concentration have been performed. Among these studies are those of: 1) Celik et al. [11] about LCA of perovskite PV cells; 2) Mohr et al. [12] regarding LCA of roof-integrated flexible amorphous silicon/nanocrystalline silicon (a-Si/nc-Si) solar cell laminates; 3) Jungbluth et al. [13] concerning 3-kW_p PV systems (mono-crystalline Si and poly-crystalline Si; slanted roof, flat roof, façade); 4) Raugei et al. [14] about the environmental profile of advanced PV modules; 5) Lamnatou and Chemisana [15] about LCA of PV-green and other roofing systems, based on ReCiPe and other methods. The results of the above mentioned studies highlight the strong dependence between the environmental performance of PV systems and their cell material.

Similarly, a number of LCA studies about high-concentration PV systems [16, 17] and small-scale CPVT (concentrating photovoltaic/thermal) can also be found in the literature. A point-focus CPVT for domestic applications has been investigated [18]. The results showed 3376 kg CO_2 emissions avoided in one year of operating the system [18]. In addition, an energy and environmental analysis of a CPVT (low-concentrating) system (installed on the roof of a building: Palermo, Italy) was conducted [19]. The EPBT (energy payback time) was found to be 0.7 years and the GWP (global warming potential) PBT was calculated to be 1 year [19].

Regarding the LCA of BIPV, functional relationships between environmental impacts of façade BIPV have been determined [20]. Moreover, Hammond et al. [21] presented a work about a mono-crystalline BIPV roof tile system (new built property; connected to the UK national grid). Furthermore, Menoufi et al. [22] evaluated a Fresnel-reflector BICPVT system by means of EI99 (Eco-indicator 99) and EPS 2000 (material manufacturing phase). Both methodologies showed that considerable environmental impact reduction is achieved by replacing the conventional BIPV configurations with the BICPV ones. The system of reference [22] was studied for the case of Lleida, Spain. Lamnatou et al. [23] conducted a study about life-cycle energy analysis and embodied carbon of a linear dielectric-based

BICPV (2D concentrator; concentrating element: dielectric asymmetric CPC; geometrical CR: 2.8×). Two configurations (with and without reflective film) were evaluated, for Exeter, Barcelona, Madrid, Dublin and Paris [23]. It was demonstrated that the use of the reflective film results in 0.2% increase in system initial impact (embodied energy, embodied carbon; phase of material manufacturing of the modules). However, on a long-term basis, this additional impact is compensated (since the configuration with reflective film has higher electrical output) and by adopting the reflective film there is a reduction of around 11–12% in EPBT and GHG (greenhouse-gas) PBT [23]. The environmental profile of the above mentioned BICPV has been also studied by using multiple Life Cycle Impact Assessment (LCIA) methods (ReCiPe, etc.) [24].

Based on the literature, it can be seen that most of the PV LCA studies are about PVs without concentration and about building-added PV systems while there are few LCA investigations on BICPV (or BICPVT) configurations [22-24]. In terms of LCIA, most of the PV LCA references concern CO_2 emissions and EPBT and there are few PV LCA studies based on the newly-developed LCIA method ReCiPe [12, 15, 24].

Given the growing importance of BICPV systems in the building sector [2], there is a need for more studies which specifically examine the environmental profiles of such systems. In the present study, the environmental performance of a dielectric-based 3D BICPV is evaluated: 1) according to different scenarios, irradiation levels, electricity mixes and LCIA methodologies, 2) by focusing on material manufacturing phase as well as by presenting results about several life-cycle stages, 3) in terms of $CO_{2.eq}$ emissions, CED (cumulative energy demand) and ReCiPe Pts per kWh of produced electricity, 4) with respect to multiple PBTs (GHG PBT, EPBT, ReCiPe PBT) and EROI (energy return on investment), 5) by presenting a comparison between the findings of the present study with results from the literature, and finally, 6) by providing a critical discussion about issues which influence the environmental performance of the proposed system.

2. MATERIALS/METHODS AND SCOPE OF THE STUDY

According to ISO 14040:2006 [25] and ISO 14044:2006 [26], the phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation are adopted.

2.1. Functional units and boundaries

The functional unit is 1 kW_p and it refers to 2.26 m^2 net PV surface and 8.2 m^2 aperture area (dimensions of one module: 1 m × 1 m). The results for the phase of material manufacturing are presented based on 1 kW_p. However, some of the life-cycle calculations are presented per kWh of produced electricity. For the life-cycle calculations, the following phases are taken into account: material manufacturing (for the modules as well as for the additional components), manufacturing of the modules, installation, use/maintenance, transportation and disposal.

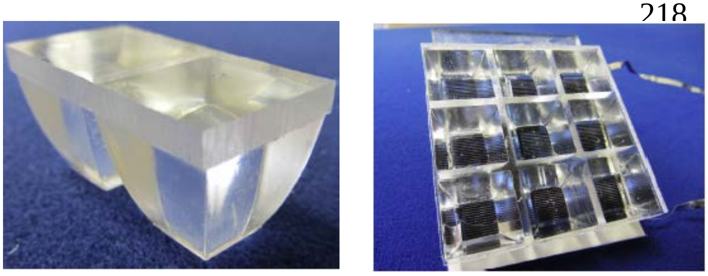
2.2. Definitions about the device which is examined

2.2.1. Technical characteristics

The studied configuration (Fig. 1) is a low-concentrating PV designed to have 3.6× geometric CR. The optical element is 3D Cross Compound Parabolic Concentrator (CCPC) made from clear polyurethane. Sylgard-184 has been used as encapsulation material for the cells [4]. The 3D design allows light to be concentrated in all the directions by means of total internal reflection. The concentrator geometry has been designed by simply sweeping a segment of parabola (about a square cross section). The refraction on its front air and dielectric interface allows achieving better external acceptance angle. Small-sized silicon solar cells based on the laser-grooved buried contact technology with an absorber area of 1 cm^2 have been used (however, any other solar cell technology (appropriate for this type of concentrating systems) may be utilised while using the same concentrating element). Experimental as well as numerical analyses have been performed verifying the optical, electrical and thermal performance of the concentrating modules. The optical analysis of the concentrator demonstrated a maximum optical efficiency of 73.4%. Moreover, a maximum power ratio of 2.67 was found when comparing the electrical output of the concentrator unit with a non-concentrating counterpart [4]. The maximum power ratio can be further enhanced to 2.73 by using a reflective film along the edges of the concentrator [5]. It should be highlighted that the proposed CPV module is appropriate for BI applications: in Fig. 1(a), a sample of a window with multiple units and components of the concentrator are illustrated. The module is suitable for integration at an incline surface (optimizing PV performance) and for integration at a vertical or horizontal surface (optimizing illumination) (Fig. 1b). In addition, the concentrator is static (it requires no solar tracking). In terms of the efficiency of the PV cells, it is 15%.

In Table 1, annual irradiance, annual electricity production, lifespan (20-years and 30-years) electricity productions, the optimal inclination angles (for Barcelona, Marseille, Seville, London, Paris and Aberdeen) and the annual optical efficiencies of the concentrator (for the studied cities) are given. Details about the assumptions for the calculation of the values which are presented in Table 1 are explained in subsection 2.2.2 and in the footnotes of Table 1. The electrical performance has been simulated from discrete experiments for all the angles of incidence range. The energetic simulations have been performed by placing the concentrating module at the optimum inclination for both optical efficiency and incoming irradiance. A detailed optical analysis has been carried out to determine the optical efficiency based on the azimuth and zenith angle. In Fig. 2(a) and 2(b), the CPV electrical DC output, depending on the site of the installation, is illustrated. It can be seen that Barcelona shows a maximum power output of around 132 kWh/kW$_p$ (January, Fig. 2a). It should be noted that the results in terms of module yearly output/performance (Table 1, Fig. 2) consider the position where the accumulated irradiance is higher over the year.

a)



b)

Figure 1. a) Components of the concentrator, c) A configuration of the BICPV system integrated at an incline surface (optimizing PV performance) and integrated at an almost horizontal surface (optimizing illumination).

Table 1. Electricity production of the studied BICPV device (for 1 kW$_p$), optimal inclination angles and annual optical efficiencies of the concentrator for the cities under study.

	Barcelona	**Marseille**	**Seville**	**London**	**Paris**	**Aberdeen**
Annual irradiance (kWh/m^2 year)	1823	1811	1993	1156	1179	1047
Electricity production[1]: kWh per year	1140	1121	1094	754	739	703
Electricity production[2]:						
kWh for 20 years lifespan	16955	16670	16278	11220	10998	10455
kWh for 30 years lifespan	24580	24166	23598	16266	15943	15157
Optimal inclination angles	37°	37°	33°	38°	35°	42°
Annual optical efficiencies	0.43	0.44	0.41	0.47	0.47	0.46

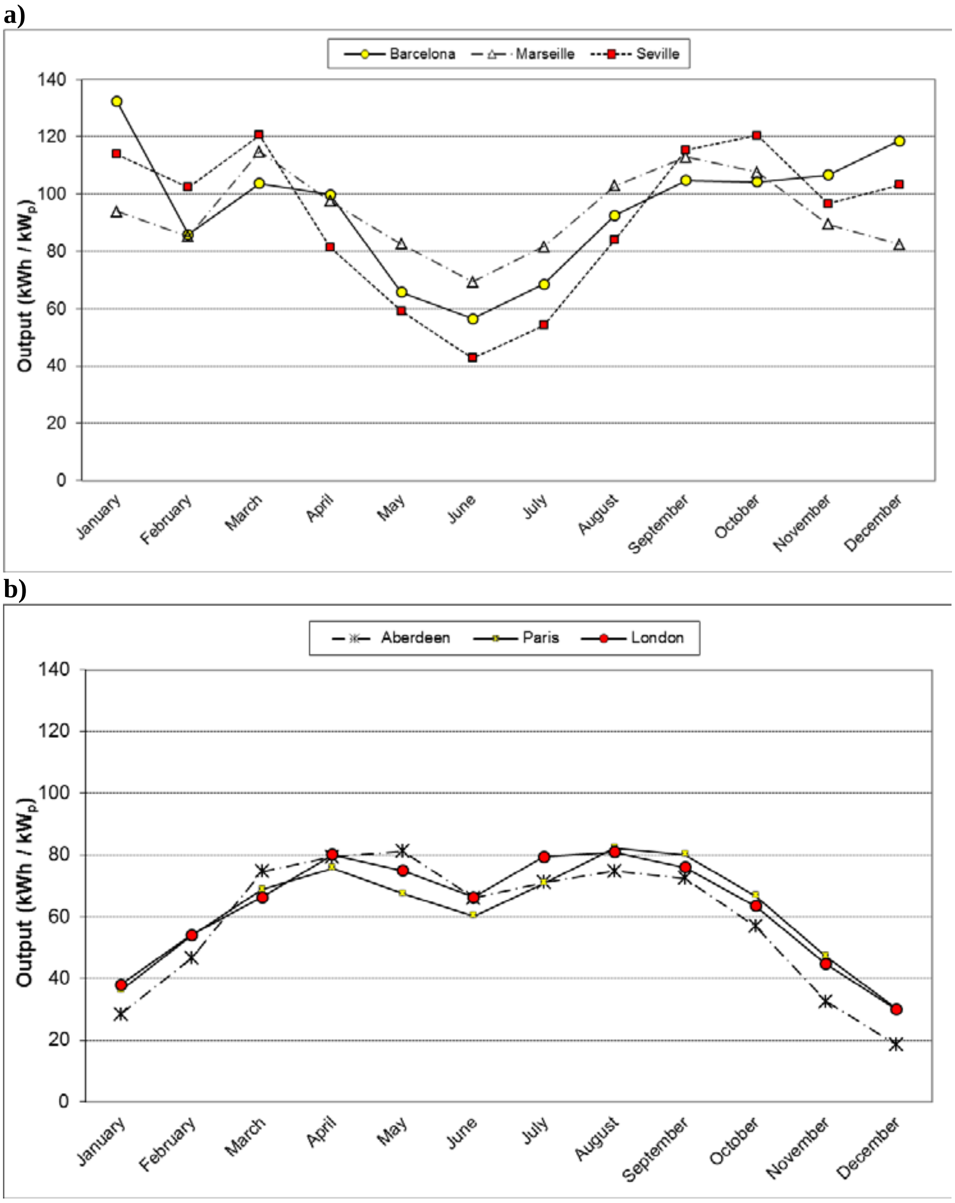


Figure 2. CPV electrical DC output (kWh/kW$_p$) per month for the following cities: a) Barcelona, Marseille, Seville and b) Aberdeen, Paris, London.

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[1] These values (laboratory conditions) consider the module DC electricity produced.

[2] These values (real conditions) include optical losses, degradation 0.7%/year and performance ratio 0.80 (details about the assumptions are presented in subsection 2.2.2).

2.2.2. Assumptions

With respect to the PV cell material, mono-crystalline PVs are adopted (ecoinvent v3.01 database [27], SimaPro 8 [28]). In terms of PV output, a degradation of 0.7% per year [29] and a performance ratio of 0.80 [20, 29] are considered. Moreover, it is assumed that the system is manufactured in Europe. Allocation has been considered.

Taking into account that the proposed configuration is BI and adapting data available in the literature to the present device, the following parts are considered for the balance-of-system (BOS): aluminium frame for the modules [14], cables and contact boxes (copper and plastics) [14]. For BOS aluminium, the adoption of recycling is assumed. The impact of the processes for module manufacturing is considered to be 27% of the impact related with manufacturing of module materials [23, 24]. The impact for the installation of the modules is assumed to be 3% of the total impact for the manufacturing of the modules and additional components [23, 24]. For the transportation (by truck) of the materials/components from the factory gate to the building and from the building to the disposal site, a distance of 50 km is assumed. For the disposal, landfill is considered. The disposal includes: 1) the components of all the modules, 2) the additional components related to the BOS and 3) the elements which are replaced over system lifetime. The use phase includes: 1) replacement of some components (replacement of the glass cover and the CCPC (once over system lifetime)) (it is assumed to be the same for the 20-years and for the 30-years lifespan), 2) general maintenance (cleaning, replacement of electronic components and cables related to the BOS (once over system lifespan), etc.: the impact of the general maintenance is considered to be 10% of material manufacturing impact of the panels [23, 24]).

Given the fact that for the calculations electricity mixes of different countries are adopted, certain results and conclusions (depending on the impact category and depending on the environmental indicator) are affected by the specific characteristics of each electricity mix. Therefore, there is a variability which is associated for example with the use of nuclear energy for electricity production. In Spain, during 2015, there was a nuclear percentage of 21.7% for covering the annual electricity needs (Spanish peninsula electricity system) (Source: Red Eléctrica de España, 2015 [30]). For the UK, according to the electricity generated in the second quarter of 2015, nuclear presented a percentage of 21.5% (Source: UK Energy Statistics, Q2 2015 [31]). On the other hand, there is a high penetration of nuclear energy (77% for the year 2014) in France´s electricity mix (Source: Électricité de France (EDF) [32]).

2.3. Life cycle inventory and sources of data

SimaPro 8 [28] and ecoinvent v3.01 database[3] [27] have been used. In Table 2, details about the materials for one module and for the additional components (related to the BOS) are presented.

Table 2. Life Cycle Inventory (LCI): materials/components of the studied BICPV device.

MATERIALS/COMPONENTS FOR ONE MODULE:	**Mass (kg per m^2 of module)**
3D CCPC (polyurethane)	14.38
PV cells (mono-crystalline silicon)	0.28
Encapsulation of the PV cells (Sylgard-184)	0.52
Cover of the module (glass)	15.00
Reflective film (silver-coated acrylic)	0.02
ADDITIONAL MATERIALS/COMPONENTS RELATED TO THE BOS:	**Mass (kg per m^2 of module[4])**
Aluminium frame for the modules [14]	1.90
Cables and contact boxes (copper) [14]	0.04
Cables and contact boxes (plastics) [14]	0.04

2.4. Life cycle impact assessment methods, environmental indicators and equations

The following LCIA methods [33] were used to assess the BICPV system:

1) Cumulative Energy Demand V1.08 / Cumulative energy demand

2) IPCC 2013 GWP 20a V1.00, IPCC 2013 GWP 100a V1.00, IPCC 2013 GWP 500a V1.00

3) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A

4) Ecological footprint V1.01 / Ecological footprint

5) USEtox (default) V1.03 / Europe 2004

6) Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A

A detailed description of the methods can be found in reference [33].

For the evaluation of the EPBT, the equation which is widely used for PVs [34] is utilised (adapted to the present system):

$$EPBT = \frac{E_{in}}{E_{out.a} - E_{O\&M.a}} = \frac{E_{mat} + E_{inst} + E_{transp} + E_{disp}}{E_{out.a} - E_{O\&M.a}} \quad (years) \tag{1}$$

where,

E_{in} is the total input (primary energy) for: the manufacturing of the materials, the modules and the additional components; the installation of the system; the transportation; the disposal of the materials/components

$E_{out.a}$ represents the annual output of the modules (converted into primary energy)

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[3] For aluminium, truck and waste treatment for copper, USLCI, LCA Food DK and EU & DK Input Output Database [28] have been utilised.

[4] The impact is calculated per m^2 of module surface. In addition, the support structure (material: steel) is not considered given the fact that the proposed CPV system is for BI applications.

$E_{O\&M.a}$ is the annual primary energy related to the use/operational phase

E_{mat} stands for the primary energy for material manufacturing (in terms of the materials for the modules and for the additional components) and module manufacturing

E_{inst} is the primary energy for the installation of the system

E_{transp} represents the primary energy for transportation of the materials/components from the factory gate to the building and from the building to the disposal site

E_{disp} refers to the primary energy for the disposal of the materials/components at the end of their life

Calculations of EROI are also presented. EROI shows how easy, in energy terms, is to exploit the available primary energy sources by investing a given amount of energy (which one already has at one's disposal) [35]. For the evaluation of EROI the following formula is adopted [35]:

$$EROI = \frac{system\ \ lifetime}{EPBT} \tag{2}$$

In the same concept with EPBT (Eq. 1), GHG PBT and ReCiPe PBT are calculated, based on the following equations:

$$\text{GHG PBT} = \frac{I_{mat} + I_{inst} + I_{transp} + I_{disp}}{I_{out.a} - I_{O\&M.a}} \qquad (years) \tag{3}$$

$$\text{ReCiPe PBT} = \frac{I_{mat} + I_{inst} + I_{transp} + I_{disp}}{I_{out.a} - I_{O\&M.a}} \qquad (years) \tag{4}$$

In Eq. (3) and Eq. (4), I_{mat}, I_{inst}, I_{transp}, I_{disp} and $I_{O\&M.a}$, represent the impact described for E_{mat}, E_{inst}, E_{transp}, E_{disp} and $E_{O\&M.a}$ regarding EPBT (Eq. 1), adapted for GHG PBT (where I stands for GHG emissions in kg $CO_{2.eq}$) and ReCiPe PBT (where I is ReCiPe impact: Pts, endpoint approach/single-score). In the same way with $E_{out.a}$ (Eq. 1), $I_{out.a}$ refers to the avoided annual impact (avoided GHG emissions or avoided ReCiPe impact, for Eq. (3) and (4), respectively) due to the use of the electricity produced by the proposed BICPV device instead of using electricity from the national grid of a country.

The PBTs (equations 1, 3 and 4) are also calculated with an alternative way since the proposed CPV is appropriate for BI applications. A BI system replaces the materials of a constructive element. In the frame of this concept, it is assumed that the studied BICPV is going to replace the materials of an inclined wall. Given the fact that there is replacement of materials, for the calculations of the PBTs with this alternative way, the impact of a wall (materials/components of a bare wall [36] that is replaced by the BICPV) is deducted from the numerator of Eq. (1), (3) and (4). The deduction from the numerator of the impact of the building materials (which are replaced by the BI solar system) has been presented by Chow and Ji [37] for the calculation of the EPBT and GHG PBT of a BIPVT system. It should be also noted that the avoided-impact approach to account for the façade systems that a BIPV configuration replaces has been presented by Perez et al. [20].

2.5. Scenarios which are examined

The performance of the BICPV is evaluated under different irradiation levels. The environmental profile of the proposed BICPV configuration is investigated for different cities (Table 1); thus, for the calculation of EPBT, EROI, GHG PBT and ReCiPe PBT the electricity mixes of Spain, France and UK are used [27, 28]. In terms of system lifespan, two scenarios are considered: pessimistic (20-years lifetime) and optimistic (30-years lifetime). Moreover, since the proposed CPV is appropriate for BI applications, scenarios with/without replacement of the materials of a wall (details are presented in section 2.4) are also examined. Furthermore, for the evaluation of the GWP, the effect of the time horizon is examined by adopting three different time horizons (20a, 100a and 500a) given the fact that certain substances (associated with GWP) gradually decompose and become inactive in a long run [33]. In this way, a broader picture of the climate change impact is provided (taking into account that the GWP over a 100-year period is the most common choice [33]).

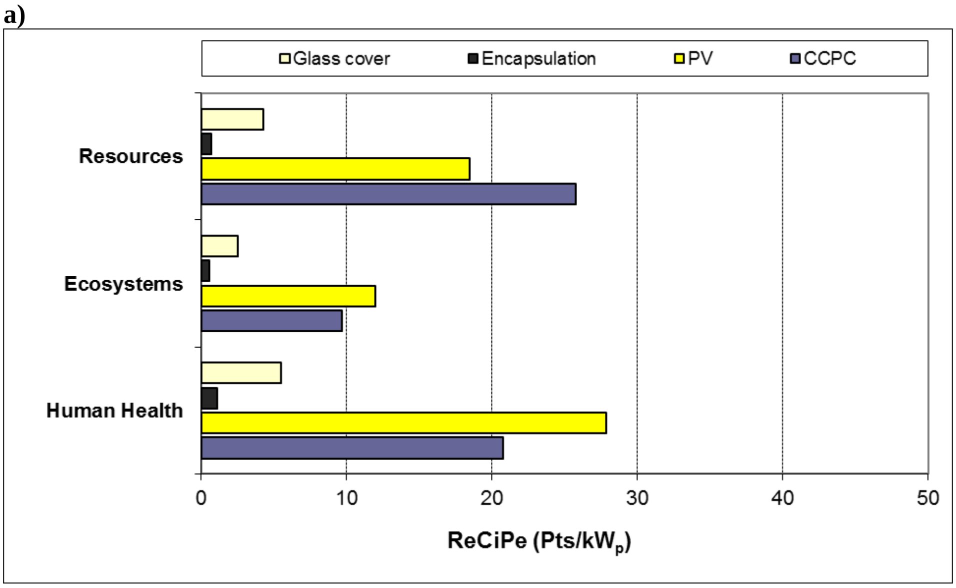
3. RESULTS AND INTERPRETATION

3.1. Phase of material manufacturing: modules

In Fig. 3, the contribution of each material/component on CPV environmental profile is illustrated (material manufacturing), based on ReCiPe (Fig. 3a) and based on EI99 (Fig. 3b). Figures 3-6 refer to the total materials/components needed for the modules for 1 kW_p (details are presented in section 2.1). The reflective film is not illustrated in figures 3-6 since it has a very small contribution to the total impact of the manufacturing of the modules (less than 0.1%, considering all the studied impact categories). However, the reflective film has been taken into account for all the calculations. From Fig. 3, it can be seen that PV cells and CCPC are the components with the highest impact, showing a contribution to the total impact ranging from 26% to 63%, depending on the impact category and the LCIA methodology.

Moreover, from Fig. 3 it can be noticed that the differences between PV and CCPC impact are more pronounced based on EI99 (Fig. 3b) than based on ReCiPe (Fig. 3a). Nevertheless, it should be noted that a direct comparison between these two methods is not possible because of their inherent differences, e.g. in terms of their endpoint characterization factors [38]. In the present LCA study, ReCiPe and EI99 are used in order to assess the results based on a newly-developed method (ReCiPe) as well as based on a classical method (EI99).

a)



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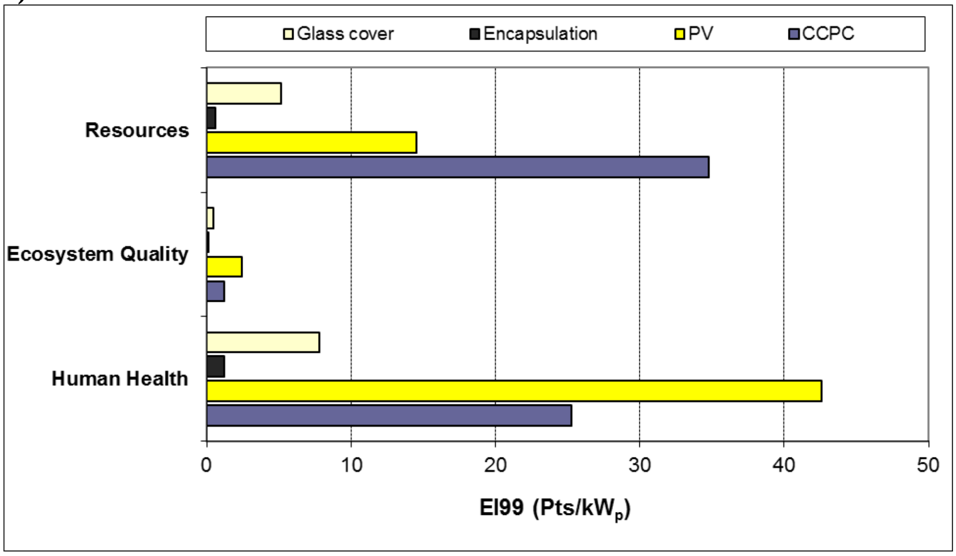
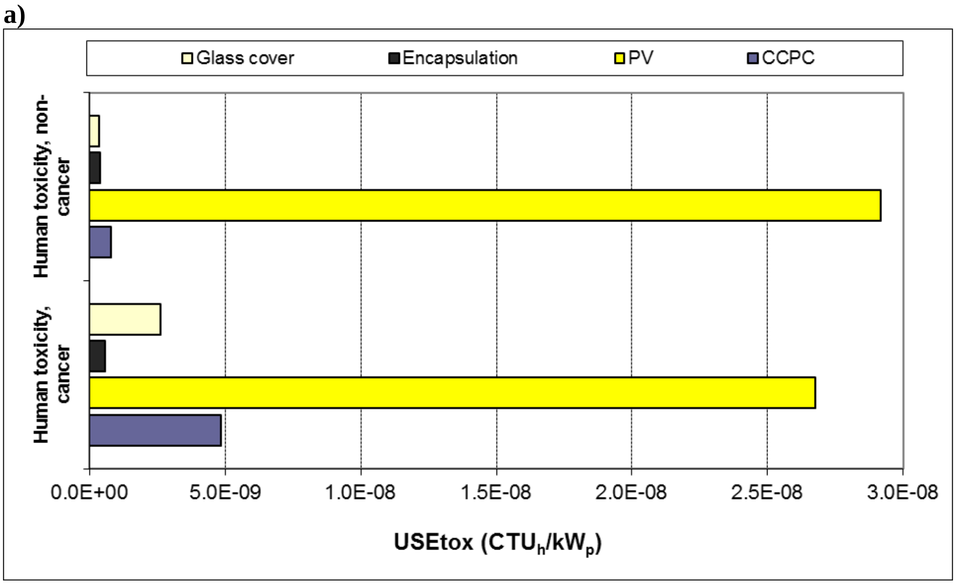


Figure 3. Material manufacturing impact of the CPV modules and contribution of each component, based on: a) ReCiPe/single-score (Pts) and b) EI99/single-score (Pts). Total materials/components needed for the modules for 1 kW$_p$.

In Fig. 4 the impact of material manufacturing (contribution of each material/component to the total impact of the proposed CPV) based on USEtox is presented. Fig. 4(a) refers to human toxicity and Fig. 4(b) concerns ecotoxicity. From Fig. 4 it can be observed that PV cells have the highest contribution to the total impact, with percentages ranging from 77% to 95%, depending on the type of toxicity.

In terms of CED and GWP (Fig. 5a and Fig. 5b), it can be observed that: 1) CCPC shows higher CED than PV cells (the contributions to the total CED are 54% and 36% for the CCPC and for the PV cells, respectively), 2) the time horizon influences the GWP results, 3) CCPC and PV cells present the major contribution to the total GWP (with percentages ranging from 40% to 48%). The differences between the findings based on GWP 20a, GWP 100a and GWP 500a are related with the different considerations adopted for each time horizon. For example, GWP 20a prioritizes gases with shorter lifetimes given the fact that it does not take into account the impacts that occur more than 20 years after the emissions happen (Source: EPA [39]).

a)



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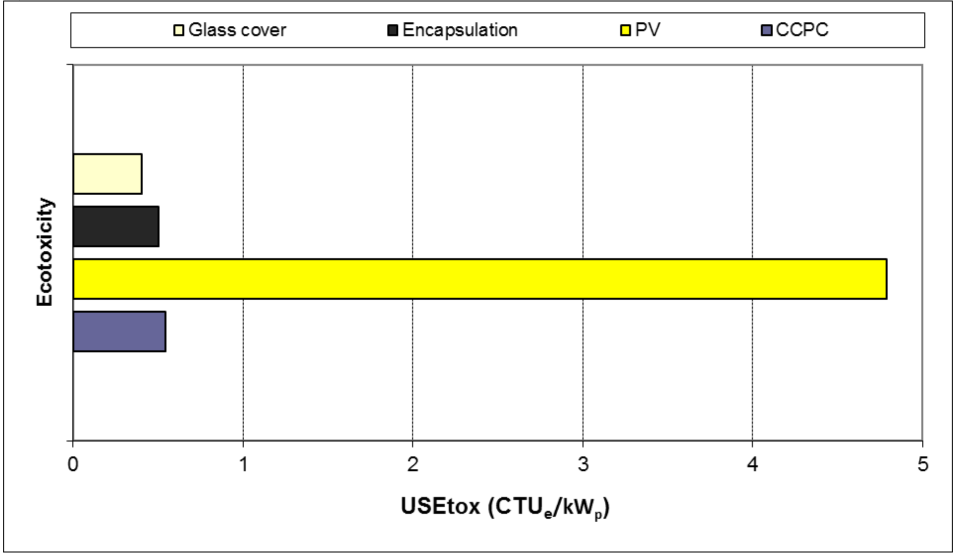


Figure 4. Material manufacturing impact of the CPV modules and contribution of each component, based on USEtox (with characterization): a) human toxicity (CTU_h) and b) ecotoxicity (CTU_e). Total materials/components needed for the modules for 1 kW_p.

Fig. 6 illustrates material manufacturing impact according to Ecological Footprint (EF) single-score results. From Fig. 6 it can be seen that carbon dioxide shows considerably higher impact Pts in comparison to land occupation and nuclear. Moreover, according to EF results, the PV cells and the CCPC are the components with the highest contributions. For example, for carbon dioxide (Fig. 6) the PV cells and the CCPC show percentages 47% and 39%, respectively.

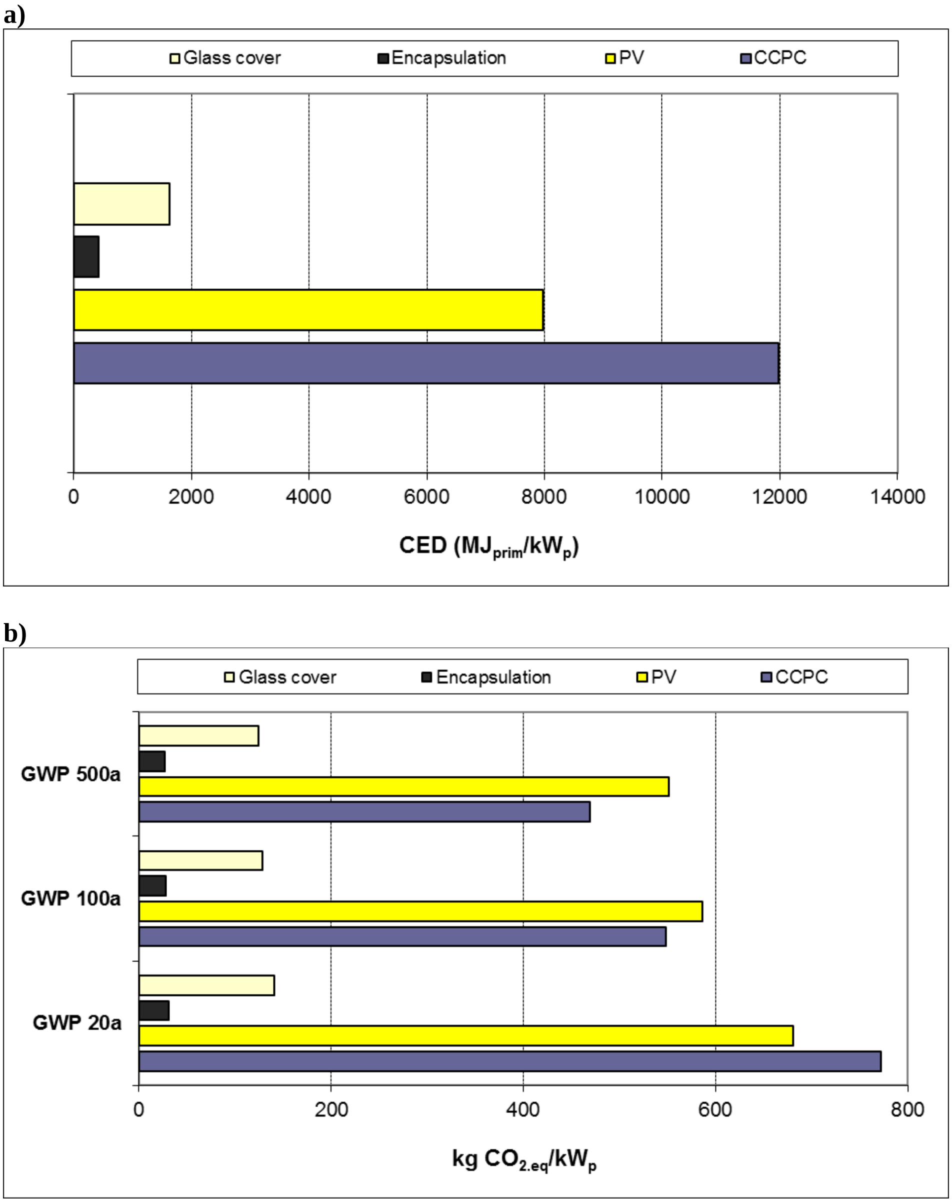


Figure 5. Material manufacturing impact of the CPV modules and contribution of each component, based on: a) CED (MJ$_{prim}$) and b) GWP 20a, GWP 100a, GWP 500a (kg CO$_{2.eq}$). Total materials/components needed for the modules for 1 kW$_p$.

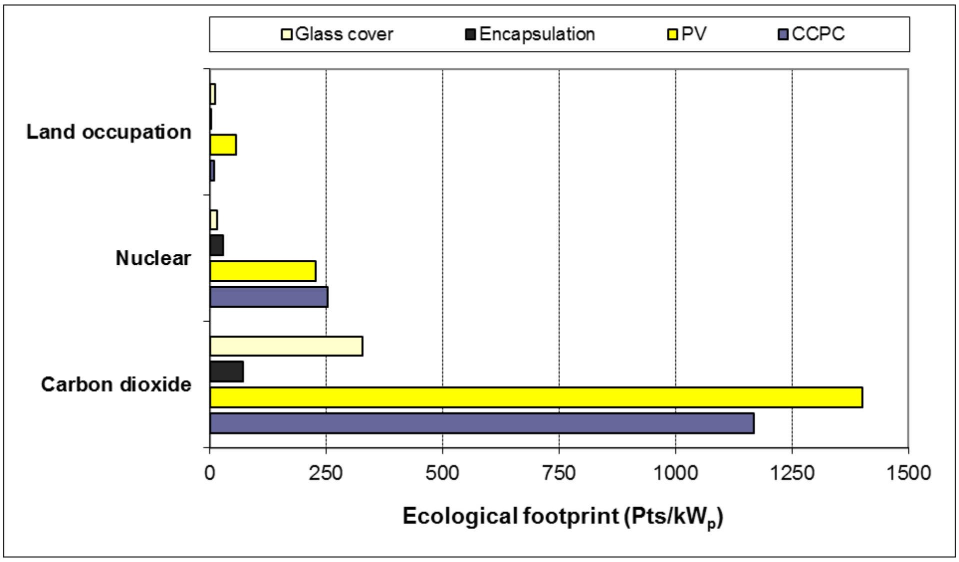


Figure 6. Material manufacturing impact of the CPV modules and contribution of each component, based on Ecological footprint/single-score (Pts). Total materials/components needed for the modules for 1 kW$_p$.

In Table 3, the percentages of the components, based on ReCiPe, EI99, USEtox, CED, GWP 20a, GWP 100a, GWP 500a and Ecological footprint (Figures 3-6), are presented.

Table 3. The contribution of PV cells, CCPC and the other components (encapsulation, glass cover and reflective film) to the total impact of the modules (based on all the components: PV cells, CCPC, encapsulation, glass cover and reflective film): Figures 3-6).

Method	**PV cells (%)**	**CCPC (%)**	**The rest of the components (encapsulation, glass cover and reflective film) (%)**
ReCiPe endpoint, single-score			
Human health	50	38	12
Ecosystems	48	39	13
Resources	37	52	11
EI99, single-score			
Human health	55	33	12
Ecosystem quality	59	28	13
Resources	26	63	11
USEtox			
Human toxicity, cancer	77	14	9
Human toxicity, non-cancer	95	3	2
Ecotoxicity	77	9	14
CED	36	54	10
GWP 20a	42	48	10
GWP 100a	45	42	13
GWP 500a	47	40	13
Ecological footprint, single-score			

Carbon dioxide	47	39	14
Nuclear	43	48	9
Land occupation	72	11	17

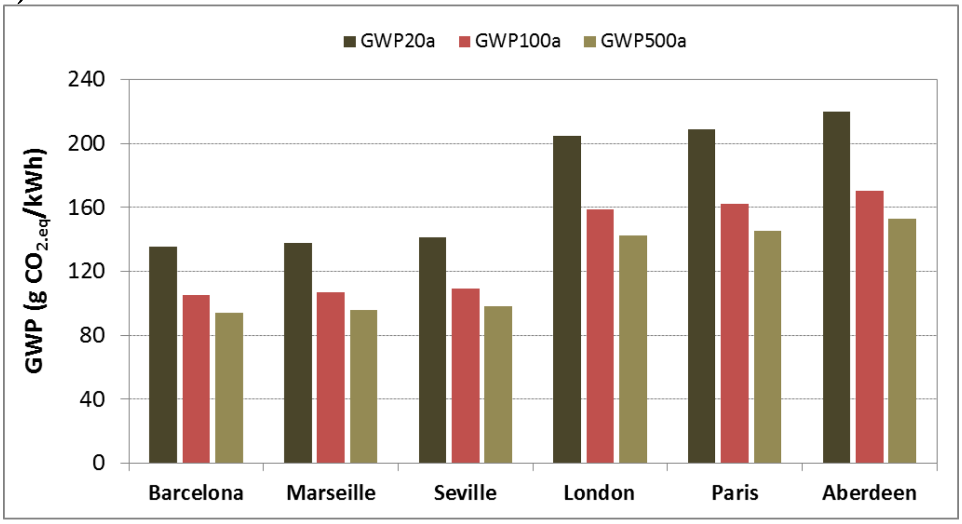
3.2. Life-cycle impact per kWh of produced electricity

The BICPV life-cycle impact[5] per kWh of produced electricity has been evaluated based on GWP, CED and ReCiPe (Fig. 7).

With respect to GWP and CED, from Fig. 7(a) and 7(b) it can be seen that: 1) the adopted time horizon influences the GWP results, 2) among the studied cities, Barcelona, Marseille and Seville show the lowest GWP and CED values (less than 142 g $CO_{2.eq}$/kWh and less than 2.9 MJ_{prim}/kWh, taking into account all the studied scenarios), 3) with 30-years lifetime (instead of 20-years) there is an impact reduction of 0.8-1.4 MJ_{prim}/kWh (considering all the studied cases), 4) London, Paris and Aberdeen present higher GWP and CED (per kWh of produced electricity) in comparison to Barcelona, Marseille and Seville (more specifically, London, Paris and Aberdeen show 159-171 g $CO_{2.eq}$/kWh (GWP 100a; 30-years scenario) and 4.07-4.36 MJ_{prim}/kWh (20-years scenario)).

Regarding ReCiPe, in Fig. 7(c) ReCiPe/single-score impact Pts per kWh of produced electricity are shown. From Fig. 7(c) it is observed that: 1) there is an impact reduction of 0.005-0.008 ReCiPe Pts/kWh by adopting 30-years lifespan (instead of 20-years), 2) Barcelona, Marseille and Seville show lower ReCiPe impact than London, Paris and Aberdeen (more analytically, for the scenario of 30-years, Barcelona, Marseille and Seville present 0.0107-0.0111 ReCiPe Pts/kWh while London, Paris and Aberdeen show 0.0161-0.0173 ReCiPe Pts/kWh).

a)



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[5] Explanations about the phases considered for the life-cycle calculations are given in section 2.1.

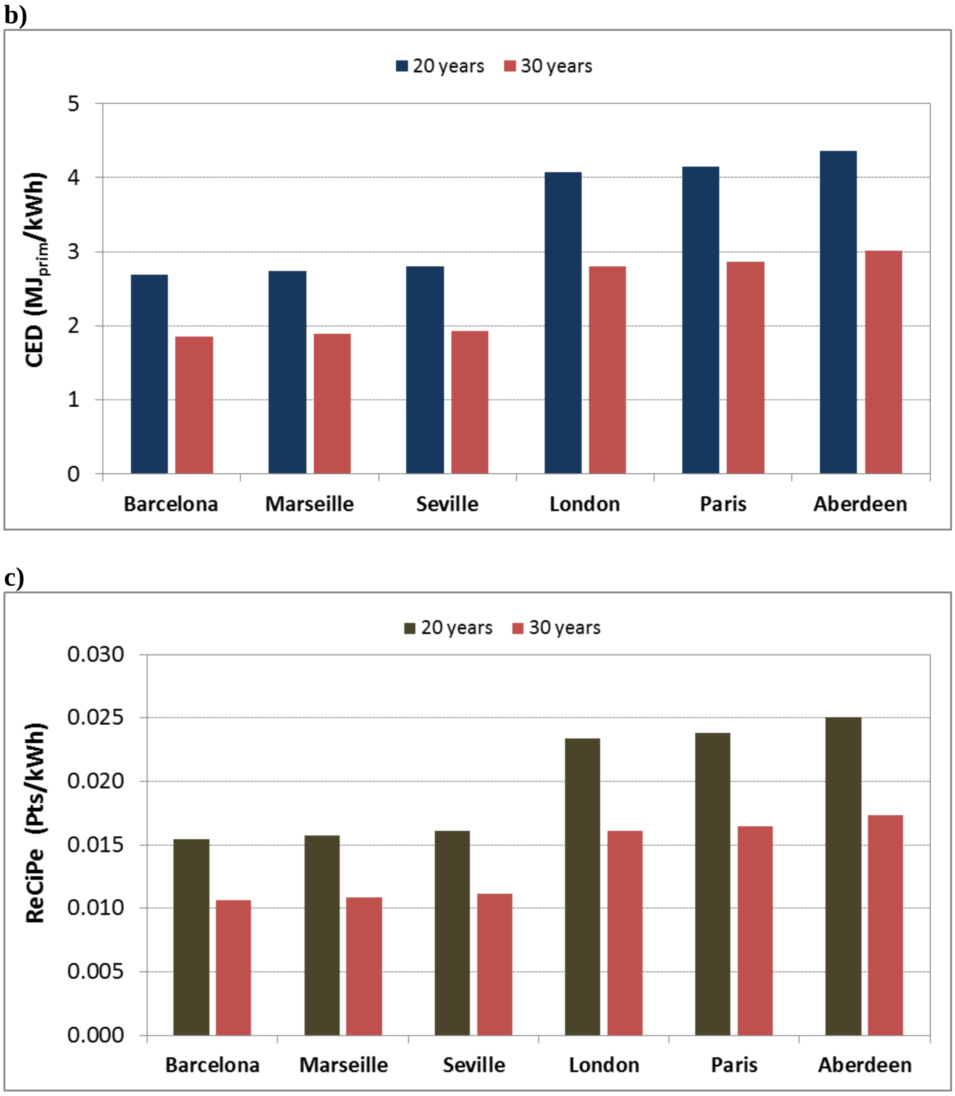


Figure 7. Life-cycle impact of the CPV per kWh of produced electricity, based on: a) GWP 20a, GWP 100a, GWP 500a (in g $CO_{2.eq}$/kWh; scenario of 30-years lifespan), b) CED (in $MJ_{primary}$/kWh; scenarios: 20-years vs. 30-years lifespan), c) ReCiPe/single-score (in Pts/kWh; scenarios: 20-years vs. 30-years lifespan).

In terms of the electricity mixes of the studied countries (SimaPro 8 [28], ecoinvent v3.01 [27]: low-voltage electricity), in Table 4 their impact is presented.

Table 4. The impact of the electricity mixes for Spain, France and UK [27, 28].

Country	**g $CO_{2.eq}$ /kWh (GWP 100a)**	**MJ_{prim}/kWh**	**Pts/kWh (ReCiPe, endpoint)**
Spain	491	9.5	0.045
France	116	12.2	0.013
UK	693	11.3	0.062

With respect to the GWP 100a, it can be seen that France electricity presents remarkably lower values in comparison to Spain and UK. This is mainly associated with the specific characteristics of France´s electricity mix (high penetration of nuclear energy, etc.: Électricité de France (EDF) [32]). It can be noticed that the electricity of France shows GWP 100a values close to those of the present BICPV for Barcelona, Marseille and Seville (Fig. 7a). However, the low $CO_{2.eq}$ emissions by an electricity mix which is based on a high penetration of nuclear energy do not imply that this electricity mix is eco-friendly. This is because nuclear power plants are often old and the risks may have a small probability to occur but they have very large effects on the environment [40]. Moreover, another environmental issue is related to the management of the nuclear waste [40]. On the other hand, the electricity mixes of Spain and UK present $CO_{2.eq}$ emissions (GWP 100a) considerably higher comparing to the GWP 100a of the BICPV for Aberdeen (the city with the highest impact among the studied cities: Fig. 7a).

Concerning CED, France´s electricity shows higher CED/kWh than the electricity of Spain and UK. By comparing the CED of the electricity mixes with the CED of the proposed BICPV (Fig. 7b), it can be observed that for example the BICPV scenario with the highest MJ_{prim}/kWh (Aberdeen, 20-years lifespan) shows around 2-3 times lower CED (in comparison to the studied electricity mixes).

Regarding ReCiPe, France´s electricity mix presents around 4-5 times lower impact than the electricity mixes of Spain and UK. More specifically, ReCiPe impact of France´s electricity is close to the BICPV scenarios with the lowest Pts/kWh (Barcelona, Marseille, Seville, 30-years lifespan: Fig. 7c). As it was previously explained, this is related with the specific characteristics of France´s electricity mix [32].

3.3. Payback times based on GHG, embodied energy and ReCiPe

Since ReCiPe is a newly-developed LCIA methodology and there are few PV LCA studies based on this method [12, 15, 24], the presentation of ReCiPe PBT, along with the widely used EPBT [14, 34, 35] and GHG PBT [19], can offer useful information (for example, comparison of the PBTs with the lifespan of the system).

In Fig. 8(a), GHG PBTs (based on Eq. 3) according to GWP 20a, GWP 100a and GWP 500a, for the scenarios with and without material replacement, are presented. Fig. 8(a) shows that: 1) by taking into account all the studied cases, Barcelona has the lowest GHG PBTs ranging from 3.23 to 3.83 years (without material replacement) and from 1.89 to 2.38 years (with material replacement); 2) material replacement results in a GHG PBT reduction of 1.3-14.5 years (with more pronounced differences (between with and without material replacement) for the French cities); 3) the GWP results are influenced by the adopted time horizon; 4) GHG PBTs for the studied cities of Spain and UK vary from 3.23 to 4.48 years (without material replacement) while for the studied French cities these values range from 17.91 to

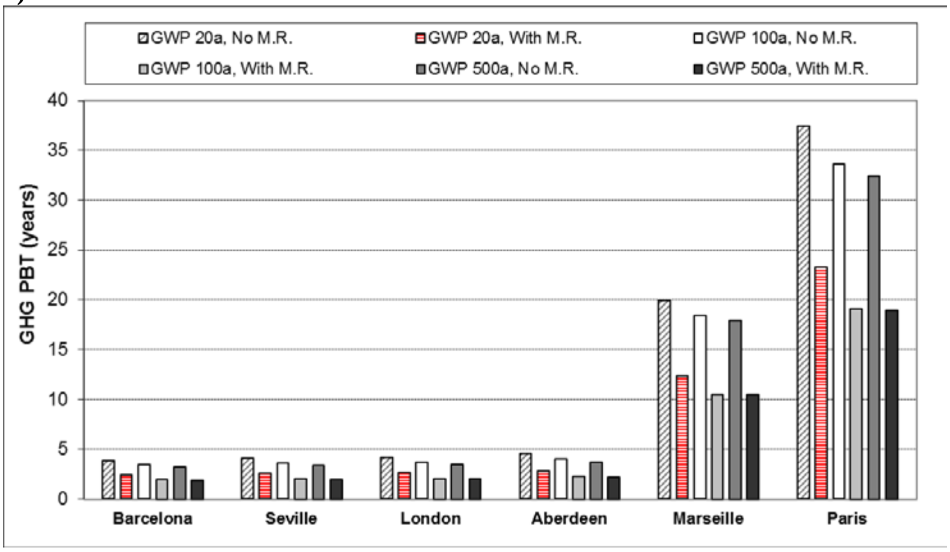
37.48 years (certainly, the high GHG PBTs for Paris and Marseille are associated with the low CO_2 emissions of France´s electricity [32]).

Fig. 8(b) illustrates the EPBTs, demonstrating that Marseille is the city with the lowest EPBT (2.3 years for the scenario without material replacement). This is related with the high CPV output for Marseille in combination with the fact that France´s electricity has higher CED/kWh in comparison with Spain and UK. On the other hand, Aberdeen has the highest EPBT (4.1 years, without material replacement) mainly due to the fact that CPV output has the lowest value for this city. With respect to material replacement, by considering this scenario there is a reduction of 0.6-1.1 years in terms of the calculated EPBTs.

Based on Fig. 8(c), it can be observed that Barcelona shows the lowest ReCiPe PBT (3.76 years, without material replacement). Moreover, the studied cities of Spain and UK present ReCiPe PBTs ranging from 3.76 to 4.53 years (without material replacement), considerably lower than the French cities (29.58 years for Paris and 16.52 years for Marseille, without material replacement). The high ReCiPe PBTs of the studied French cities are associated with the low avoided ReCiPe impact ($I_{out.a}$ of Eq. 4) for Paris and Marseille (certainly, this is related to the specific characteristics of France´s electricity [32]). On the other hand, by taking into account all the studied cities, material replacement reduces ReCiPe PBTs 2.5-19.8 years (with more pronounced reductions for the French cities).

By taking into account all the studied cases of Fig. 8, it can be seen that for some cases certain GPBT and ReCiPe PBT values for Paris exceed the assumed lifespan of the system (20 and 30 years). On the other hand, EPBT for all the studied cases shows values considerable lower than system lifespan.

a)



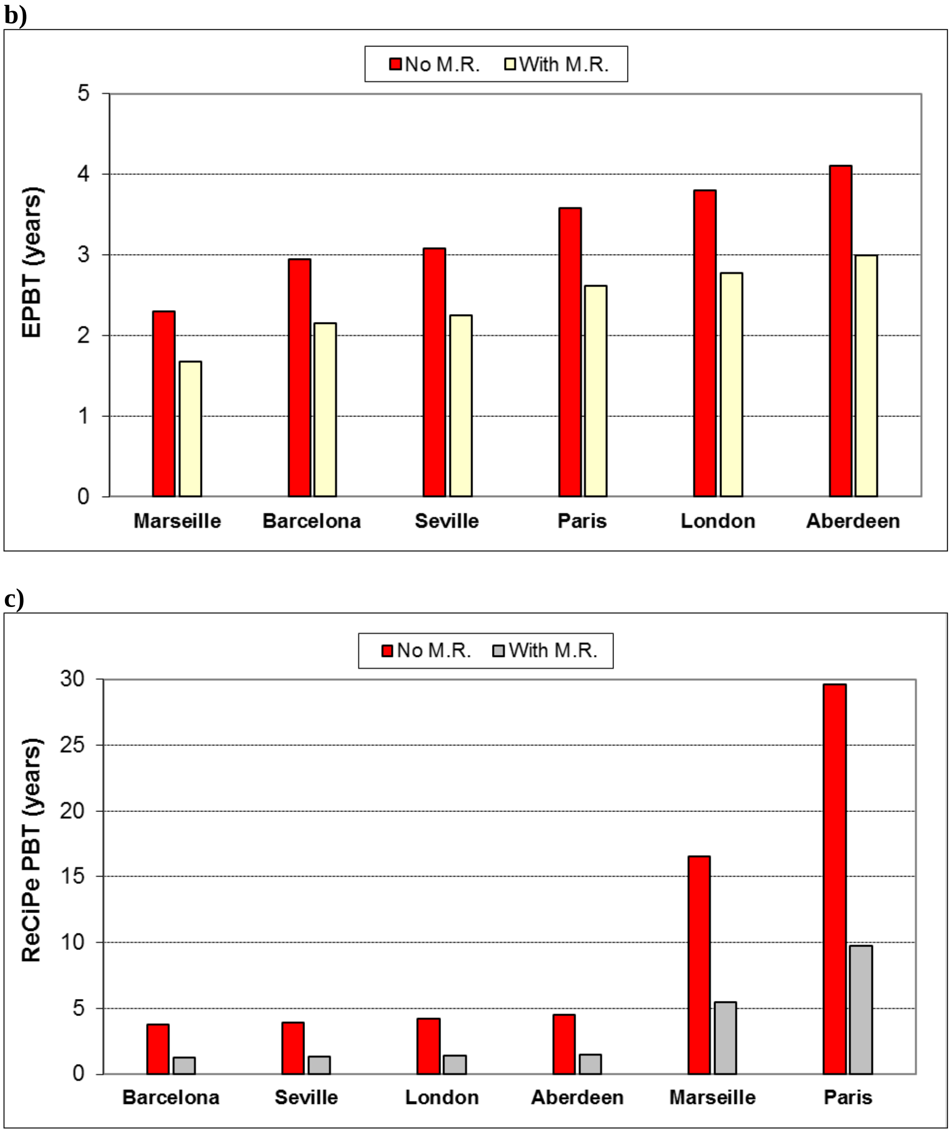


Figure 8. PBTs (in years) of the CPV: a) GHG PBT (based on GWP 20a, GWP 100a and GWP 500a), b) EPBT and c) ReCiPe PBT. Scenarios: with vs. without Material Replacement (M.R.).

The above mentioned GHG PBT, EPBT and ReCiPe PBT findings are close to the results of the studies [23, 24] for a linear dielectric-based BICPV. In reference [23], EPBTs around 1.8-2.4 years for Barcelona/Madrid and 2.4-3.5 years for Paris, Exeter and Dublin were presented. Moreover, for Exeter, Dublin, Barcelona and Madrid, GHG PBTs 3.3-5.7 years were found while for Paris the calculated GHG PBTs were 27.2–33.1 years [23]. With respect to ReCiPe PBT, the above mentioned linear dielectric-based BICPV for Barcelona, Dublin and Exeter showed ReCiPe PBTs ranging from around 3.6 to 4.4 years [24].

3.4. Energy return on investment (EROI)

The findings about EROI (Fig. 9) reveal that: 1) the adoption of 30-years lifetime (instead of 20-years) results in EROI increase of around 2-6, 2) the consideration of material replacement increases

EROI approximately 2-5, 3) Marseille has the highest EROI (as it is expected since it has the lowest EPBT) ranging from around 9 to 18 (depending on the scenario), 4) Aberdeen shows the lowest EROI (since it has the highest EPBT) varying from around 5 to 10, 5) for all the cases EROI is higher than 1. By considering that the high EROI of an energy production process is crucial in terms of its long-term viability [35], EROI results (Fig. 9) show that the present BICPV has the highest long-term viability for Marseille and the lowest for Aberdeen. In the investigation of Raugei et al. [35] (according to Eq. (2) and for 30-years lifespan and 1700 kWh/m^{2}year insolation as average southern European ground-level insolation), an EROI value of 19 was presented for a mono-c Si rooftop PV system.

It should be highlighted that for the calculations of the PBTs (and also for EROI since EROI is based on EPBT) there is an uncertainty related to the electricity mixes. For the evaluation of the PBTs there is conversion of the CPV output into avoided impact according to the electricity mix of a certain country ($E_{out.a}$ and $I_{out.a}$: equations 1, 3 and 4). In order to reduce this uncertainty, perspectives such as modelling the electricity system to identify which type of production is avoided when CPV electricity is produced could be adopted [24].

Another source of uncertainty may arise for example due to the resource indicator (e.g. depending on the reserve option of the LCIA method) and/or due to health and ecosystem indicators (for example, depending on how nuclear risk and radioactivity are accounted for in these indicators) [24].

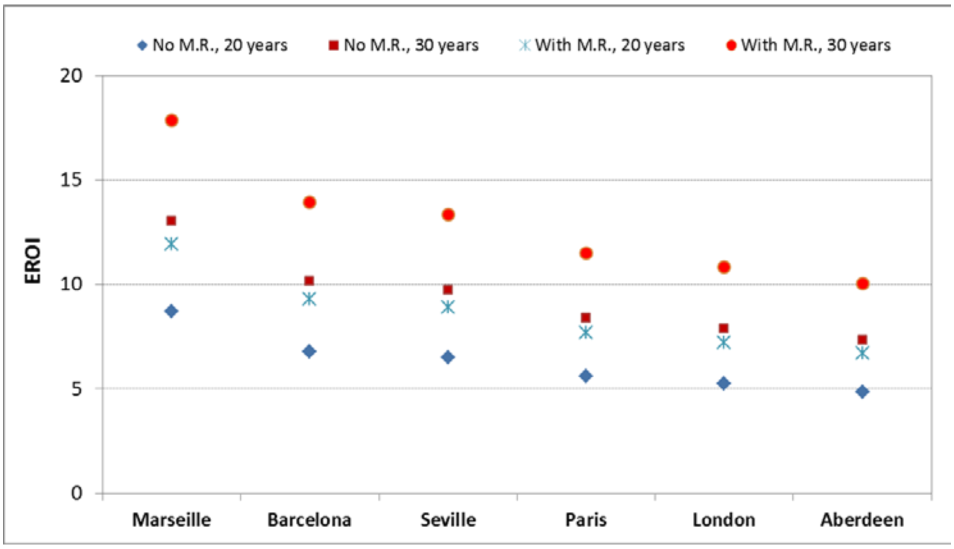


Figure 9. EROI of the CPV. Scenarios: 1) 20-years vs. 30-years lifespan and 2) with vs. without Material Replacement (M.R.).

3.5. Issues which influence the environmental profile of the proposed BICPV system

There are multiple parameters which influence the performance (from environmental point of view) of a BICPV system. These parameters refer to:

- The total mass and the material of the concentrator (since the PV cell material is replaced by the material of the concentrator [2]).
- The total mass of the aluminium for the frame (taking into account that the production of aluminium products is energy intensive).
- The CR of the CPV (considering that for BI applications are more suitable systems with CR less than 10× [2]).
- The adoption of a static concentrator (it should be taken into account that for low CR, a static concentrator can be used [2]).
- The type of building integration (façade integration, roof integration, etc.), considering that for some cases building integration (except of the advantages which offers: higher aesthetic value in comparison with a building-added solar system [24], etc.) results in a reduction of the efficiency of the solar system (certainly, the reduction of the efficiency influences the environmental profile of the system).
- The tilt angles and the orientations.
- The latitude and the solar radiation for a specific region/country [23].
- The electricity mix of a country (since for the calculation of certain environmental indicators it is necessary the conversion of the PV output into avoided impact based on coefficients for the electricity mix of a country). For that case there are several limitations related e.g. with the percentage of nuclear energy into the electricity mix of a country [23, 24].

By taking into account the above mentioned critical issues which influence BICPV systems, the environmental profile of the proposed BICPV system can be improved by means of:

- The adoption of a concentrator with lower mass and lower impact.
- The reduction of the optical losses of the concentrator.
- The utilisation of less aluminium for the frame (or use of alternative materials with lower impact).
- The increase of the CR. However, there are some limits in terms of CR increase. In the literature there is a study about the effect of the CR on the environmental performance of a BICPVT, by using EI99 [22]. A sensitivity analysis for different CRs was presented and it was highlighted that increasing the CR results in a reduction of the environmental impact of the BICPVT. Nevertheless, it was mentioned that this requires further analysis and confirmation, considering PV cell efficiency and optical efficiency under

different CRs during operational phase. Moreover, it was noted that the increase of the CR is associated with higher optical losses [22].

- The utilization of materials/components with higher lifetime in order to increase the lifetime of the whole system.

At this point it should be noted that the degree of influence of the above mentioned parameters depends on the specific case that is examined (type of BICPV which is going to be evaluated, location where the system is going to be installed, etc.).

4. COMPARISONS WITH THE LITERATURE AND DISCUSSION

In Table 5 comparisons with the literature are presented. From Table 5 it can be seen that when considering impacts per kW_p the present BICPV shows lower impact than other PV installations without concentration. On the other hand, the comparisons based on kWh show that, for example, when comparing ReCiPe Pts of the present system with [27, 28, 41], the proposed BICPV has 0.002-0.004 Pts/kWh higher impact. Moreover, by comparing GWP 100a findings of the present study with the results based on [27, 28, 41], it can be seen that the present system shows 0.04-0.06 kg $CO_{2.eq}$/kWh higher impact.

At this point it should be noted that these comparisons are not direct due to differences between the present study and the other studies (differences in terms of the assumptions, the boundaries, the secondary data, data quality, etc.). Thereby, there are some limitations in terms of the comparisons presented in Table 5. Concerning the functional unit, in the work of Fthenakis et al. [34] it is noted that the functional unit determines the function based upon which comparisons can be made for PV and other electricity-generating systems. With respect to kW_p as functional unit, in reference [34] it was highlighted that kW_p (rated power) is utilized in order to quantify the environmental impact of electrical parts, including inverter, transformer as well as wire, grid connection and grounding devices. The kW_p units can be also adopted as the reference flow in order to quantify the environmental impact of module technologies. Nevertheless, the comparisons between module technologies should not be based on the nominal power (kW_p) since the amount of kWh provided to the grid may differ between the studied systems [34].

Certainly, the proposed BICPV shows lower impact per kW_p than the PV systems without concentration due to the fact that there is less PV cell material (the PV cell material has been replaced by the material of the solar concentrator). However, by evaluating the impact per kWh, the proposed BICPV presents higher impact (details about the differences between the present study and the results based on

[27, 28, 41] were previously mentioned) than most of the examined BIPV systems without concentration. Nevertheless, it should be taken into account that the present system also provides other functions, except of electricity production (e.g. illumination control in the interior space of the building), which limit its performance from electrical point of view. Thus, as a future prospect could be the increase of the optical efficiency of the system in order to achieve better PV output and in this way, better performance from environmental point of view. Nevertheless, the increase of the optical efficiency of the system will decrease the performance of the system in terms of the illumination control.

With respect to the behavior of the BIPVs in different locations, it should be mentioned that BIPV systems present higher energy output potential in high latitudes because the sun altitude angles are lower. In this way, the angles of incidence with respect to the vertical façade are lower and thus, there is higher irradiance on the PVs. Further information can be found in the study [43].

Table 5. Results based on the present BICPV device and results from the literature.

	PRESENT STUDY (BICPV)	**LITERATURE STUDIES**
ReCiPe	Life-cycle Pts (endpoint; 30-years lifespan):	BIPV, single-Si, façade installation [27, 28, 41][6]
	0.0107 Pts/kWh for Barcelona	0.0087 Pts/kWh for Barcelona
	0.0109 Pts/kWh for Marseille	0.0090 Pts/kWh for Marseille
	0.0111 Pts/kWh for Seville	0.0083 Pts/kWh for Seville
	0.0161 Pts/kWh for London	0.0131 Pts/kWh for London
	0.0165 Pts/kWh for Paris	0.0128 Pts/kWh for Paris
	0.0173 Pts/kWh for Aberdeen	0.0147 Pts/kWh for Aberdeen
		BA PV Mohr et al. [12] (centre of Netherlands) ReCiPe (endpoint approach): overall damage score 0.01 ecopoints/kWh for a multi-Si PV system (roof-mounted)
	ReCiPe (endpoint; phase of manufacturing: materials, modules and additional components): 172 Pts/kW$_p$	PV slanted-roof, SimaPro 8 [28], ecoinvent v3.01 [27], PV slanted-roof, single-Si, {GLO}, market: ReCiPe 309 Pts/kW$_p$
GWP	Life-cycle GWP 100a (30-years lifespan):	BIPV, single-Si, façade installation [27, 28, 41]
	0.105 kg $CO_{2.eq}$/kWh for Barcelona	0.070 kg $CO_{2.eq}$/kWh for Barcelona
	0.107 kg $CO_{2.eq}$/kWh for Marseille	0.072 kg $CO_{2.eq}$/kWh for Marseille
	0.110 kg $CO_{2.eq}$/kWh for Seville	0.066 kg $CO_{2.eq}$/kWh for Seville
	0.159 kg $CO_{2.eq}$/kWh for London	0.105 kg $CO_{2.eq}$/kWh for London
	0.162 kg $CO_{2.eq}$/kWh for Paris	0.102 kg $CO_{2.eq}$/kWh for Paris
	0.171 kg $CO_{2.eq}$/kWh for Aberdeen	0.117 kg $CO_{2.eq}$/kWh for Aberdeen
		Flat façade-mounted PVs, Jayathissa et al. [42] (Frankfurt, Germany):
		0.195 kg $CO_{2.eq}$/kWh for the poly-Si
		0.166 kg $CO_{2.eq}$/kWh for the CIGS
		0.144 kg $CO_{2.eq}$/kWh for the CdTe
	GWP 100a (phase of manufacturing: materials, modules and additional components): 1.7 t/kW$_p$	PV-slanted-roof, SimaPro 8 [28], ecoinvent v3.01 [27], PV slanted-roof, single-Si, {GLO}, market: GWP 100a 2.5 t/kW$_p$

5. CONCLUSIONS

The environmental performance of a dielectric-based 3D BICPV device is presented. Multiple scenarios and LCIA methodologies (ReCiPe, etc.) are utilized. Several environmental indicators are

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[6] These calculations are based on the impact of BIPV SimaPro 8 [28], ecoinvent v3.01 [27], PV façade installation, single-Si, {GLO}, market and the PV output for BIPV from PVGIS [41].

calculated for different cities: Paris, Marseille, Barcelona, Seville, Aberdeen and London. In this way, the present study provides a wide range of environmental indicators for a specific type of BICPV.

The results of material manufacturing phase reveal that PV cells and CCPC are the components with the highest contribution to the total impact, based on ReCiPe, EI99, USEtox, CED, GWP 20a, GWP 100a, GWP 500a and EF.

Among the studied cities, Barcelona, Marseille and Seville present the lowest GWP, CED and ReCiPe impact per kWh of produced electricity: 1) less than 142 g $CO_{2.eq}$/kWh and less than 2.9 MJ_{prim}/kWh (taking into account all the studied scenarios), 2) 0.0107-0.0111 ReCiPe Pts/kWh (ReCiPe endpoint; 30-years lifespan).

In addition, GHG PBT and ReCiPe PBT show considerably higher values for the studied French cities in comparison to the studied cities of Spain and UK. This is mainly related with the specific characteristics of France´s electricity mix. On the other hand, EPBT has the lowest value for Marseille (2.3 years for the scenario without material replacement) which is related with: 1) the high CPV output for this city, 2) the high CED of France´s electricity mix. Thereby, Marseille shows also the highest EROI value.

It should be noted that certain results/conclusions, depending on factors such as the impact category and the environmental indicator, include uncertainties. Thus, a future prospect of the present study could be an uncertainty analysis based on critical parameters which considerably influence the profile of the proposed system. Another future prospect could be the improvement of some aspects in terms of system design in order to reduce the impact per kWh of produced electricity. However, given the fact that the proposed system has multiple functions (production of electricity, illumination control, etc.) the increase of the PV output by means of optical efficiency improvement means decrease of the capacity of the system in terms of illumination control.

Conclusively, given the fact that BICPV systems are a new tendency in the building sector and there are few BICPV LCA studies, the present article provides useful information about the environmental profile of the proposed device.

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