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# Environmental assessment of a building-integrated linear dielectric-based concentrating photovoltaic according to multiple life-cycle indicators

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## ABSTRACT

Building-integrated concentrating photovoltaic systems are of great interest, offering several advantages for building and environment. The present study is an advancement towards the life-cycle assessment of a linear dielectric-based building-integrated concentrating photovoltaic system by means of multiple life-cycle impact assessment methods and environmental indicators (ReCiPe, Eco-indicator 99, ecological footprint, USEtox, ReCiPe-based and Eco-indicator 99-based payback times, etc.), providing a detailed analysis. Two configurations (with and without reflective film) are examined, for different cities (Barcelona, Exeter and Dublin). By focusing on material manufacturing (system with reflective film), in general, ReCiPe (endpoint/single-score; points) results are in accordance to Eco-indicator 99 (single-score; points) findings and based on both methods PVs have the maximum contribution for ecosystems/ecosystem quality and human health. Moreover, based on USEtox results, there is a remarkable difference between the footprint of PVs and the impact of the other components. With regard to the payback times, taking into account both configurations with/without reflective film, Barcelona presents the lowest ReCiPe and Eco-indicator 99 PBTs ranging from 3.6 to 5.8 years. On the other hand, Exeter and Dublin show PBTs from 3.7 to 7.8 years. According to ReCiPe/endpoint results with

characterization, for climate change/human health (system with reflective film) Barcelona shows $1.2 \times 10^{-7}$ disability-adjusted-life-years per kWh while Dublin and Exeter present a footprint of about $1.8 \times 10^{-7}$ disability-adjusted-life-years per kWh. Results in terms of (species.yr)/kWh are also presented (ReCiPe/endpoint with characterization), for several scenarios. Regarding the two configurations, the findings based on multiple approaches verify that reflective film considerably improves the eco-profile of the reference system (configuration without reflective film). For example, by utilizing reflective film there is a reduction of ReCiPe-based and Eco-indicator 99-based payback times ranging from 0.5 to 0.9 years, depending on the scenario. Finally, results from the literature are presented along with results of the present study and a critical discussion is provided. Conclusively, the proposed LCA model can also be applied to similar systems, providing useful information about their environmental profile and offering the possibility to select among different configurations the best from ecological/cleaner production point of view.

*Keywords: Life Cycle Assessment (LCA); Building-Integrated Concentrating PV (BICPV); ReCiPe; Eco-indicator 99 (EI99); Ecological footprint; USEtox*


**LIST OF ABBREVIATIONS AND SYMBOLS**

a-Si: amorphous silicon

BI: Building Integrated

BICPV: Building-Integrated Concentrating Photovoltaic

BIPV: Building-Integrated Photovoltaic

BOS: Balance of System

CML-IA: CML-IA method

CPC: Compound Parabolic Concentrator

CPV: Concentrating Photovoltaic

CR: Concentration Ratio

DALY: Disability Adjusted Life Years

EF: Ecological Footprint method

EPS 2000: EPS 2000 method

EI99: Eco-Indicator 99 method

EI99 PBT (in years): Payback time based on EI99 method

$I$: the total ReCiPe/endpoint single-score (Pts) or the total EI99 single-score (Pts)[1]

LCA: Life Cycle Assessment

LCIA: Life Cycle Impact Assessment

nc-Si: nanocrystalline silicon

PBT: Payback Time

Pts: points

PV: Photovoltaic

ReCiPe: ReCiPe method

ReCiPe PBT (in years): Payback time based on ReCiPe method (Eq. 1)

$R_{x.EI99}$: a ratio which quantifies the relationship between EF and EI99 (Eq. 2)

$R_{x.ReCiPe}$: a ratio which quantifies the relationship between EF and ReCiPe (Eq. 3)

USEtox: USEtox method

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[1] regarding: material manufacturing of modules and additional system components ($I_{mat}$), installation ($I_{inst}$), transportation ($I_{transp}$), disposal ($I_{disp}$), avoided annual impact due to the use of CPV electricity instead of using national grid electricity ($I_{out.a}$), annual impact during use phase ($I_{O\&M.a}$)

## 1. INTRODUCTION

In the field of Photovoltaic (PV) technology, Concentrating PV (CPV) systems with Concentration Ratio (CR) less than 10× are appropriate for Building-Integrated (BI) applications, offering multiple advantages in comparison to flat-plate PV panels without concentration. Chemisana (2011) conducted a critical review about BICPV, highlighting CPV benefits: higher electrical conversion efficiency in the PV cells, reduced use of toxic products related with the manufacture of the PV cells, etc. The above mentioned benefits along with an aesthetically pleasing design[2] make BICPV systems interesting for the building sector. Thus, there is a need for increased use of CPV for small-scale BI applications.

In the literature, there are experimental as well as modelling studies about CPV systems appropriate for BI applications. A linear asymmetric Compound Parabolic Concentrator (CPC) with a geometrical CR of 2.8× was evaluated by Baig et al. (2014). The initial experiments showed a maximum power ratio of 2.2 compared to a non-concentrating counterpart system. An increase of 16% in the average power output was attained by using a configuration with reflective film. Recently, they also studied the impact of solar spectrum on this system (Baig et al., 2016). In addition, Baig et al. (2015) evaluated the performance of a BICPV (6× geometrical CR) carrying out detailed modelling and indoor experiments. The system included a dielectric-based symmetric elliptical hyperboloid concentrating element attached to a silicon solar cell. Using the non-uniform flux distribution obtained by the optical analysis, the electrical modelling of the solar cell was performed at different incident angles. Modelling demonstrated a maximum power ratio of 3.7 which was in line with the experimental values under a constant solar cell temperature.

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[2] Fig. 1 shows details about the BICPV system studied in the present work, verifying the advantages of BICPV technology from aesthetical point of view (Fig. 1d).

Other studies within the field of dielectric-based BICPV are those of: 1) Zacharopoulos et al. (2000) (three-dimensional optical analysis of two dielectric, non-imaging concentrating covers for BIPVs was conducted and the results verified that an asymmetric concentrator is more suitable for use at building façades), 2) Mallick et al. (2006) (based on an experimental comparison, non-concentrating and asymmetric BIPVs with CPC, were examined; for the BIPV with CPC, a power ratio of 1.62 measured compared to a similar non-concentrating PV with the same cell area), 3) Sarmah and Mallick (2015) (design, fabrication and outdoor performance analysis of a low-concentrating PV system appropriate for BI applications was conducted; details about the results of Sarmah and Mallick (2015) are presented in section 2.2.1).

Additionally, in the literature there are some studies about the evaluation of PV environmental performance by adopting Life Cycle Assessment (LCA). LCA is a structured/comprehensive method of quantifying material- as well as energy-flows and their associated emissions in the life-cycle of a product (Fthenakis et al., 2011). Fthenakis et al. (2011) proposed methodology guidelines on PV LCA. Furthermore, Fthenakis and Kim (2013) performed LCA about large-scale, high-concentrating PV systems. Mohr et al. (2013) conducted an LCA study about roof-integrated flexible amorphous silicon/nanocrystalline silicon (a-Si/nc-Si) solar cell laminates. A comparison of a PV system based on a-Si/nc-Si PV with a roof-mounted multi-Si PV system was also presented. ReCiPe method was adopted and the results showed overall damage scores for the a-Si/nc-Si PV and the multi-Si PV system of 0.012 and 0.010 ecopoints/kWh, respectively (Mohr et al., 2013). Jungbluth et al. (2005) investigated several configurations of 3-kW$_p$ slanted-roof PV systems (mono-crystalline and poly-crystalline Si cells). The PBT for the indicators non-renewable and non-renewable plus hydro cumulative energy demand was found to be 3-6 years for the different PV

configurations studied. The PBT based on EI99 (Eco-indicator 99) was also evaluated and it was found that it is slightly higher than the energy-demand one. Lamnatou and Chemisana (2014; 2015) performed LCA about PV-green and other roofing systems. Raugei et al. (2007) investigated advanced PV modules and, furthermore, Alsema and Nieuwlaar (2000) studied the energy viability of PV systems. Nishimura et al. (2010) presented an LCA about high-concentration PV power generation systems and Desideri et al. (2012) performed an LCA about a ground-mounted 1778 kW$_p$ PV plant. Dufo-López et al. (2011) conducted a study about multi-objective optimization minimizing cost and life-cycle emissions of stand-alone PV–wind–diesel systems (with battery storage). Goe and Gaustad (2014) presented an energy-payback analysis about PV recycling. Lakhani et al. (2014) investigated land use impacts for life-cycle cost analysis of energy systems. A case of California's PV implementation was examined (Lakhani et al., 2014).

Concerning LCA about BIPV and BICPV configurations, Hammond et al. (2012) presented a whole systems appraisal of a BIPV configuration, based on energy, environmental and economic evaluations. The functional unit was a 2.1 kW$_p$ mono-crystalline BIPV roof tile system (25-years lifetime) installed on a new built property and connected to the UK national grid. A displaced energy Payback Time (PBT) of 4.5 years was found. Perez et al. (2011) investigated façade BIPVs. Functional relationships between environmental impacts of façade BIPV under a range of incident radiation and under a range of applications were determined (Perez et al., 2011). Menoufi et al. (2013) evaluated a Fresnel-reflector BICPV system (phase of material manufacturing), by means of EI99 and EPS 2000, for the climatic conditions of Lleida (Catalonia, Spain). Both methods revealed that considerable environmental impact reduction is achieved by

replacing a conventional BIPV configuration with the BICPV scheme (Menoufi et al., 2013).

Based on the literature review, it can be seen that the majority of the PV LCA investigations refer to PVs without concentration. Moreover, most of the studies are about building-added systems while there are few LCA studies about BICPV. Thereby, it may be seen that there is a gap within the field of BICPV LCA which can be addressed by newly-developed Life Cycle Impact Assessment (LCIA) methods such as ReCiPe. In the review article of Gerbinet et al. (2014) about PV LCA, it is noted that the most commonly used method is EI99 while ReCiPe, which is the most up-to-date method, is not yet largely utilised.

The present work, by utilizing different methods than those adopted in authors´ previous study (Lamnatou et al., 2015), provides an in-depth analysis about the proposed linear dielectric-based BICPV system by evaluating its environmental profile by means of multiple environmental indicators and LCIA methods, with emphasis on the newly-developed LCIA method ReCiPe (PRé, 2014). More specifically, the goals of the present work are:

1) Extension of authors´ previous investigation which was based on embodied energy and embodied carbon, by adopting ReCiPe, EI99, USEtox, Ecological Footprint (EF), ReCiPe-based and EI99-based PBTs

2) Presentation of additional results regarding avoided ReCiPe and EI99 impact during use phase of the proposed BICPV system

3) Evaluation of DALY (disability adjusted life years) impact (ReCiPe/endpoint with characterization) for several stages of system life-cycle (material manufacturing, installation, use, transportation, disposal)

4) Calculation of the impact (ReCiPe/endpoint with characterization) in terms of human health (DALY) and ecosystems (species.yr) per kWh of produced electricity

5) Assessment of the environmental profile of the system for different cities and CPV configurations (with and without reflective film), confirming the findings of authors´ previous LCA by means of additional LCIA methods/environmental indicators

By taking into account the differences between the present investigation and the other studies of the literature, it can be seen that the present work: 1) along with authors´ previous LCA presents an evaluation of the environmental profile of the proposed BICPV system based on multiple approaches, 2) evaluates the system not only in terms of its manufacturing phase but also in terms of several stages of its life-cycle, 3) provides results based on the newly-developed LCIA method ReCiPe along with results based on classical methods, giving emphasis on ReCiPe findings since there are few studies in the literature about PV LCA by means of ReCiPe (Mohr et al., 2013; Lamnatou and Chemisana, 2015), 4) takes into account the effect of different climatic conditions (Barcelona, Exeter, Dublin) on the environmental profile of the proposed BICPV system and 5) presents ReCiPe/endpoint (with characterization) impact in DALY/kWh and (species.yr)/kWh (in the literature there are few PV LCA investigations which show ReCiPe/endpoint (with characterization) DALY/kWh for PV systems (Hirschberg et al., 2014)).

Given the importance of LCA within the building sector (Peng, 2016) and in general for products which consist of many parts made of different materials (Zhang et al., 2015), the proposed LCA model can offer useful information for the design of

small-scale CPV systems which have practical applications in the building sector, selecting the most eco-friendly configuration within the concept of cleaner production.

## 2. MATERIALS AND METHODS

The implementation of the LCA follows ISO 14040 (2006) and ISO 14044 (2006). The phases adopted are: 1) goal and scope definition, 2) life-cycle inventory, 3) life-cycle impact assessment and 4) interpretation.

### 2.1. Functional unit and system boundaries

In the present study, the functional unit of 1 $kW_p$, which includes 43 modules (3.86 $m^2$ net PV surface; 10.53 $m^2$ aperture area), is used. The phases of material manufacturing (for the modules and additional system components), manufacturing of the modules, installation, use/maintenance, transportation and disposal are considered as life-cycle calculations.

### 2.2. Definition of the system
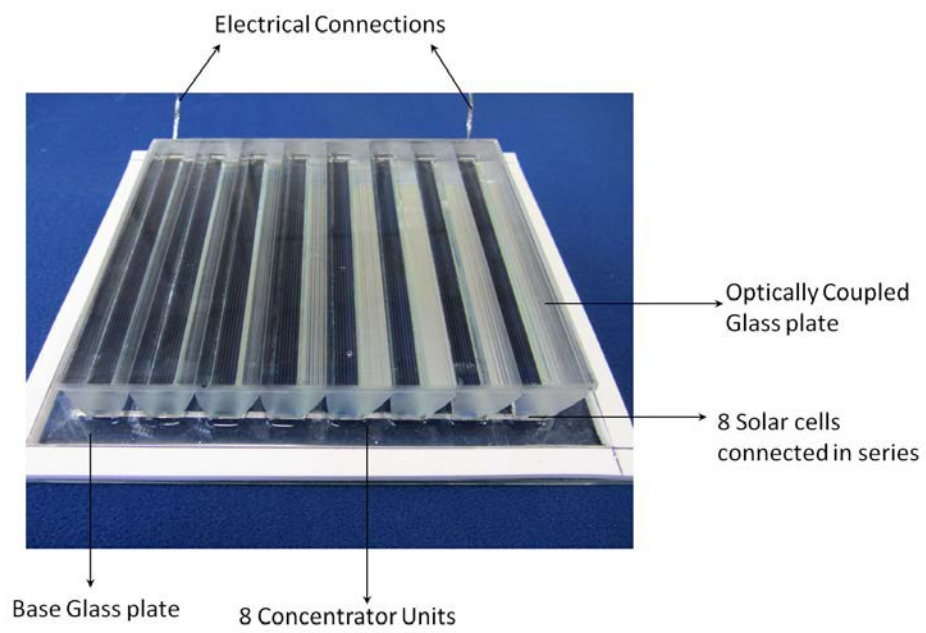*2.2.1. Technical characteristics*

In Fig. 1, the studied system is illustrated. It is a linear concentrating PV essentially consisting of a linear (line-axis) concentrator element attached to a solar cell using encapsulation (Sylgard-184) and placed between two glass sheets. The PV cells (mono-crystalline silicon) have 15% efficiency and the concentrating element is a dielectric asymmetric CPC with acceptance half angles ($0^o$ & $55^o$). The geometrical CR of the proposed CPV is 2.8× and the concentrator design is two-dimensional. The main application of the proposed system is to be used as double-glazed BICPV (details can be found in the study of Baig et al. (2014)). In Fig. 1(a) and (b), a sample of the concentrator element (polyurethane) and the solar cell utilised, are presented. One of the problems in the system was that the incoming sunlight rays were leaking at the encapsulant interface which was rectified by using a reflective film. In Fig. 1(c), the

configuration with reflective film is illustrated, showing the trapping of the rays (which results in PV output increase). Moreover, in Fig. 1(d) a configuration of the proposed BICPV integrated into the façade of a building is presented, showing the aesthetical aspect jointly with its shading effect. The module is considered to be vertically placed on a south-facing wall.

In Table 1, the annual electricity production of the two configurations is given. From Table 1 it can be observed that reflective film results in an increase of PV annual output around 11%. The data refer to three cities: Exeter, Barcelona and Dublin. It should be noted that the monthly performance of the CPV is simulated from discrete experiments for all the angles of incidence range. The meteorological data used are based on a typical meteorological year (Meteonorm files from TRNSYS software: TRNSYS 16). In addition, PV orientation is south and PV inclination is vertical ($90^{o}$).

The proposed BICPV (configuration with reflective film) has been characterised in Edinburgh (outdoor characterisation for different weather conditions) and its performance has been compared to a similar non-concentrating counter-part flat-plate module (with the same PV cell area and technology) in real time (Sarmah and Mallick, 2015). The maximum power output of the CPV on a day with sunny intervals was 2.27 times higher than that for the flat-plate system. Thereby, for façade-integrated applications (under real weather conditions), it has been experimentally verified that the proposed BICPV outperforms an equivalent non-concentrating flat-plate PV system (Sarmah and Mallick, 2015).
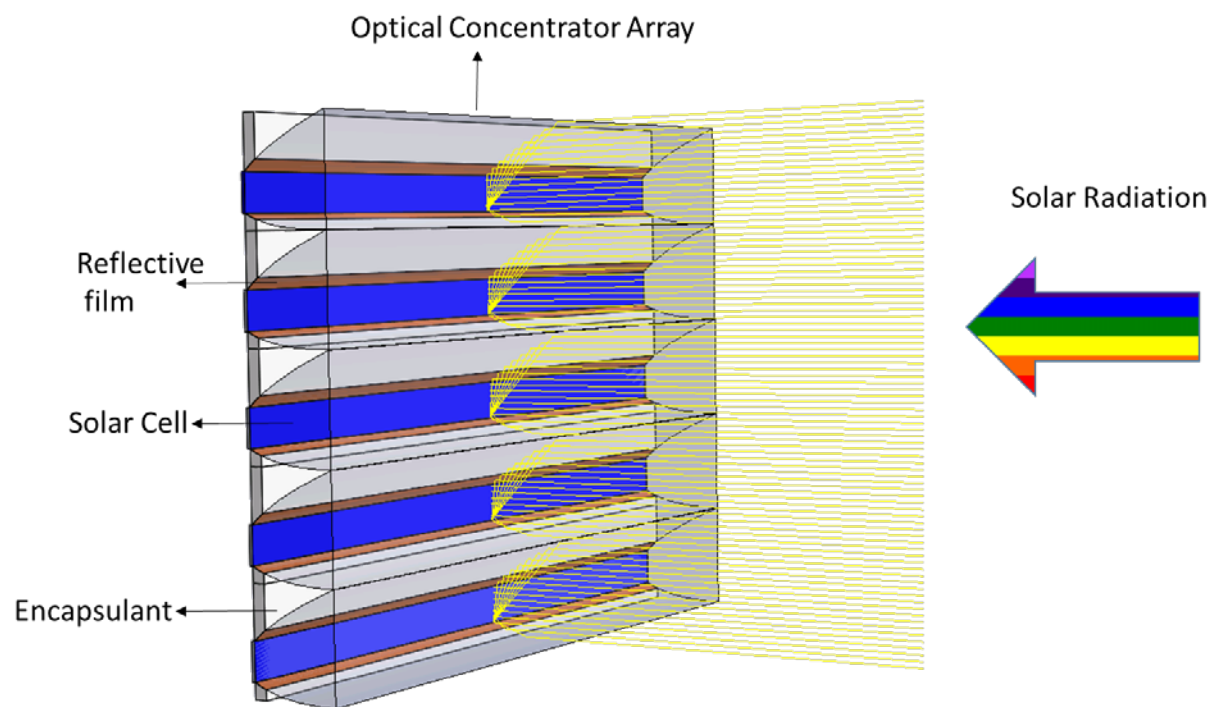
**a)**



Electrical Connections

Optically Coupled Glass plate

8 Solar cells connected in series

Base Glass plate

8 Concentrator Units

**b)**

**c)**



Optical Concentrator Array

Solar Radiation

Reflective film

Solar Cell

Encapsulant

**d)**



**Figure 1.** a) Sample of the concentrator element made by using polyurethane, b) Solar cell used in the system, c) Configuration with reflective film along the edges showing the trapped rays, d) A configuration of the proposed BICPV system integrated into the façade of a building.

**Table 1.** Electricity production (kWh per year) of the BICPV system (1 kW$_p$) for: Exeter, Barcelona and Dublin.

| System | Production of electricity (kWh/year) | | |
|---|---|---|---|
| | Exeter | Barcelona | Dublin |
| No reflective film (reference system) | 1092.20 | 1580.68 | 1075.79 |
| With reflective film | 1227.86 | 1774.39 | 1214.04 |

*2.2.2. Assumptions*

For the calculation of the PV output, only the losses of the CPV system are taken into consideration (Lamnatou et al., 2015). For studying the impact of the PV cells, mono-crystalline PV laminates are considered (Source: SimaPro 8/ecoinvent 3 database). The additional components of the system include: aluminium frame and cables/contact boxes (copper; plastics) for the balance-of-system (BOS) (Raugei et al., 2007). Recycling is assumed for BOS aluminium frame.

The impact of the processes for module manufacture is incorporated into the LCA model as 27% of the impact that is related with the manufacture of module materials. Furthermore, the impact of system installation is included as 3% of the total impact for the manufacture of the modules and additional components. Moreover, system use phase refers to: replacement of some components (over lifetime: one replacement of the glass cover and one replacement of the CPC) as well as general maintenance (cleaning, etc.). The impact of the general maintenance is assumed to be 10% of material manufacture impact of the panels (Lamnatou et al., 2015).

For the transportation phase, there is transportation of the materials/components from the factory gate to the building and from the building to the disposal site (50 km; transportation by truck).

For the phase of disposal, landfill is assumed and disposal includes the components of all the modules, additional system components and elements which are replaced over system lifespan.

At this point it should be noted that certain results/conclusions (depending on the impact category/environmental indicator) are influenced by the adopted electricity mixes. Thus, it should be taken into account that there is an uncertainty which is related e.g. with the utilisation of nuclear energy for electricity production. For example, in

Spain, during 2015, there was a nuclear percentage of 21.7% for covering the annual electricity demand (Spanish peninsula electricity system) (Source: Red Eléctrica de España, 2015). With respect to the UK, based on the electricity generated in the second quarter of 2015, nuclear accounted for 21.5% (Source: UK Energy Statistics, Q2 2015). On the other hand, Ireland does not have nuclear power in its domestic electricity generation mix (Source: Ireland's Transition to a Low Carbon Energy Future).

## 2.3. Life cycle inventory

SimaPro 8/ecoinvent 3 database[3] are used for the evaluation of the environmental profile of the proposed BICPV system. In Table 2, the materials/components of the studied BICPV (with reflective film) are presented. Table 2 refers to the materials needed for one module as well as to the additional components in terms of the BOS (Raugei et al., 2007).

**Table 2.** Materials/components for the life-cycle inventory of the BICPV system with reflective film.

| MATERIALS/COMPONENTS FOR ONE MODULE: | Mass (kg per module) |
|---|---|
| CPC (polyurethane) | 3.6075 |
| PV cells (mono-crystalline silicon) | 0.0650 |
| Encapsulation of the PV cells (Sylgard-184) | 0.5150 |
| Cover of the module (glass) | 3.0250 |
| Reflective film (silver-coated acrylic) | 0.0156 |
| **ADDITIONAL MATERIALS/ COMPONENTS IN TERMS OF THE BOS:** | **Mass (kg per m$^2$ of module[4])** |
| Aluminium frame | 1.90 |
| Cables and contact boxes (copper) | 0.04 |
| Cables and contact boxes (plastics) | 0.04 |

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[3] For few cases, USLCI, LCA Food DK and EU & DK Input Output Database (Source: SimaPro 8) are also 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 is for BI applications.

**2.4. Life cycle impact assessment methods used for the present study**

Multiple LCIA methods are utilised (Source: SimaPro 8) in order to provide a complete picture of the studied issues. More specifically, the LCA model is based on:

1) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (single-score as well as with characterization results are presented)

2) Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A (single-score results)

3) USEtox (default) V1.03 / Europe 2004 (with characterization results)

4) Ecological footprint V1.01 / Ecological footprint (single-score as well as with characterization results are presented)

With respect to the adopted methods, ReCiPe is successor of EI99 and CML-IA. The purpose at the start of the development was to integrate the 'problem oriented approach' of CML-IA and the 'damage oriented approach' of EI99. Regarding USEtox, the USEtox model is an environmental model for the characterization of human and eco-toxicological impacts in the context of LCIA and comparative risk assessment investigations. In addition, EF presents the biologically productive land and water a population requires to produce the resources it consumes as well as to absorb part of the waste generated by fossil and nuclear fuel consumption. Concerning characterization, in the frame of LCA studies, the EF of a product is the sum of time integrated direct and indirect land occupation, related to nuclear energy use and to $CO_2$ emissions from fossil energy utilization (PRé, 2014).

With reference to PBT, in accordance with the concept of energy PBT for PVs (Fthenakis et al., 2011; Raugei et al., 2007), ReCiPe PBT (Lamnatou and Chemisana, 2015) is evaluated by means of the following equation:

$$\text{ReCiPe PBT} = \frac{I_{mat} + I_{inst} + I_{transp} + I_{disp}}{I_{out.a} - I_{O\&M.a}} \quad (years) \tag{1}$$

Where $I$ is the total ReCiPe/endpoint single-score (points: Pts) regarding: material manufacturing of modules and additional system components ($I_{mat}$), installation ($I_{inst}$), transportation ($I_{transp}$), disposal ($I_{disp}$), avoided annual impact due to the use of CPV electricity instead of using national grid electricity ($I_{out.a}$), annual impact during use phase ($I_{O\&M.a}$). In addition, EI99 PBT is evaluated in accordance with Eq. (1), based on EI99 single-score (Pts).

On the other hand, the ratio $R_{x.EI99}$ of the $EF_x$ (EF with characterization; results in m$^2$a ("a" represents "year")) and $EI99_x$ (single-score results in ecopoints) is evaluated based on Eq. (2) (Huijbregts et al., 2008). $R_{x.EI99}$ quantifies the relationship between EF (as a relative simple environmental indicator) and EI99 (as a relative complex environmental indicator) (Huijbregts et al., 2008).

$$R_{x.EI99} = \frac{EF_x}{EI99_x} \tag{2}$$

In accordance with Eq. (2), $R_{x.ReCiPe}$ is also calculated based on the results of $EF_x$ (with characterization; m$^2$a) and ReCiPe (single-score; Pts):

$$R_{x.ReCiPe} = \frac{EF_x}{ReCiPe_x} \tag{3}$$

## 2.5. Adopted scenarios

Concerning system lifespan, three scenarios are evaluated: pessimistic (20-years lifetime), realistic (25-years lifetime) and optimistic (30-years lifetime). Regarding the proposed BICPV system, two configurations (with reflective film and without reflective film (reference system): Fig. 1c) are examined. Moreover, the environmental profile of the system is evaluated for different cities (Barcelona, Exeter and Dublin) in order to

investigate the effect of different climatic conditions and electricity mixes[5] (Spain, UK and Ireland).

## 3. RESULTS AND DISCUSSION

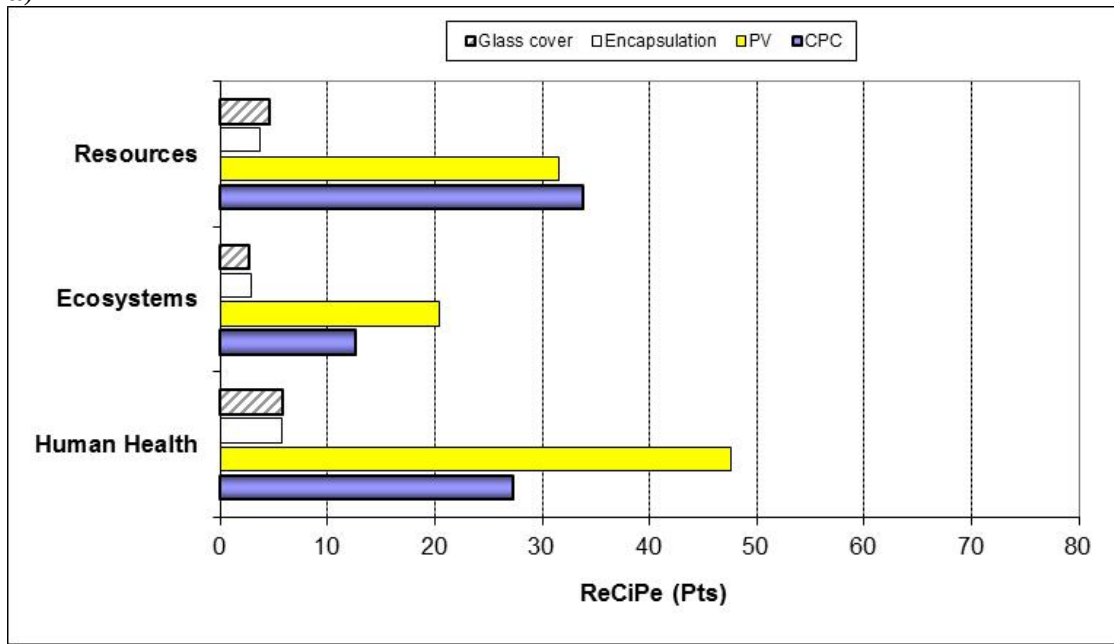### 3.1. Material manufacturing of the modules: CPV with reflective film

The contribution of each material/component on the total impact of the proposed BICPV is examined based on ReCiPe/single-score, EI99/single-score, USEtox/characterization, EF/single-score and ReCiPe/characterization (Figures 2-5). The calculations regard material manufacturing of the 43 modules and it should be noted that in Figures 2-5 are presented all the components except of reflective film. This is because reflective film has low contribution to the total impact of the modules (less than 0.3%, based on all the adopted methods and impact categories). However, for the calculations, all the components including reflective film have been taken into account.

In terms of ReCiPe/single-score and EI99/single-score, from Fig. 2(a) and 2(b) it can be seen that, in general, ReCiPe findings are in accordance with EI99 results. More specifically, for both methods, the component with the maximum contribution for resources is CPC (45.9% for ReCiPe and 57.8% for EI99) while for ecosystems/ecosystem quality and human health, PVs have the highest contribution (with percentages ranging from around 53% to 63%, for both methods).

At this point it should be noted that in the present LCA, ReCiPe and EI99 are both adopted in order to verify the results based on a newly-developed method (ReCiPe) as well as based on a classical method (EI99). A direct comparison between these two methods is not possible due to their inherent differences, for example in terms of their endpoint characterization factors (Goedkoop et al., 2009).

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[5] Uncertainties associated with the adopted electricity mixes are discussed in the assumptions.
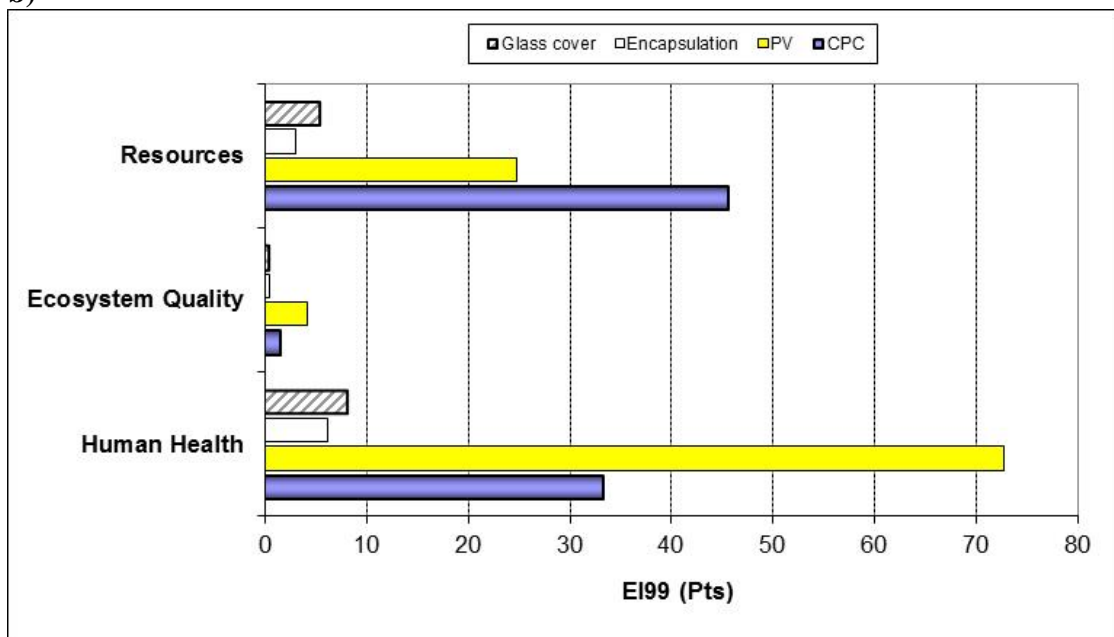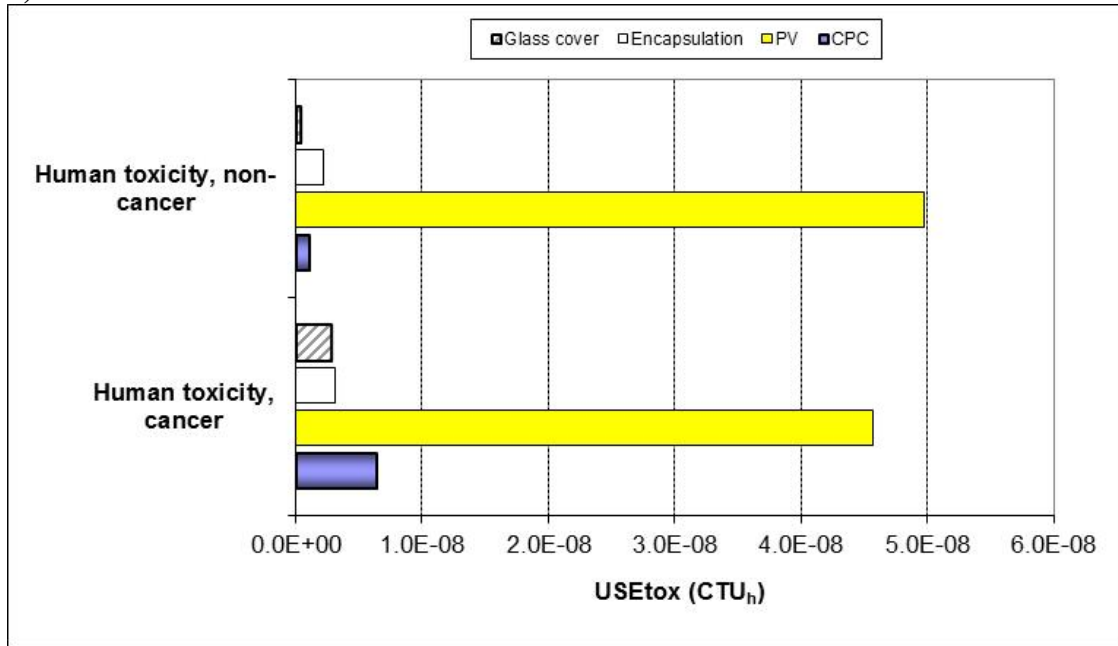
**a)**



**b)**



**Figure 2.** The contribution of each material/component to the total impact of CPV material manufacturing (43 modules; configuration with reflective film), based on: a) ReCiPe/single-score (Pts) and b) EI99/single-score (Pts).

In addition, in Fig. 3 USEtox/characterization results are illustrated for human toxicity/non-cancer (Fig. 3a), human toxicity/cancer (Fig. 3a) and ecotoxicity (Fig. 3b). For all the above mentioned categories, PVs have the highest contribution, with percentages ranging from 68.3% to 93.3% (thus, based on USEtox results, there is a remarkable difference between the footprint of PVs and the impact of the other components).

Regarding EF/single-score (Fig. 4), land occupation shows lower scores in comparison to nuclear and carbon dioxide. With respect to the categories of nuclear and carbon dioxide, PVs and CPC are the components with the highest footprint. From Fig. 4 it can be also observed that carbon dioxide presents noticeably higher impact in comparison to the other two categories (land occupation and nuclear).

Furthermore, calculations are also conducted based on ReCiPe/endpoint with characterization. In Fig. 5, DALY-based results are presented revealing that for all the components of the CPV system, climate change/human health, particulate matter formation and human toxicity are the categories with the highest footprint. Among these three categories, climate change/human health shows the highest contribution to the total impact (for all the components) with percentages ranging from 58% to 83% of the total DALY impact (based on the six studied categories presented in Fig. 5: climate change/human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation). Moreover, by taking into account the total DALY footprint of all the studied categories of Fig. 5, it can be observed that PVs are responsible for the greatest part of DALY impact.
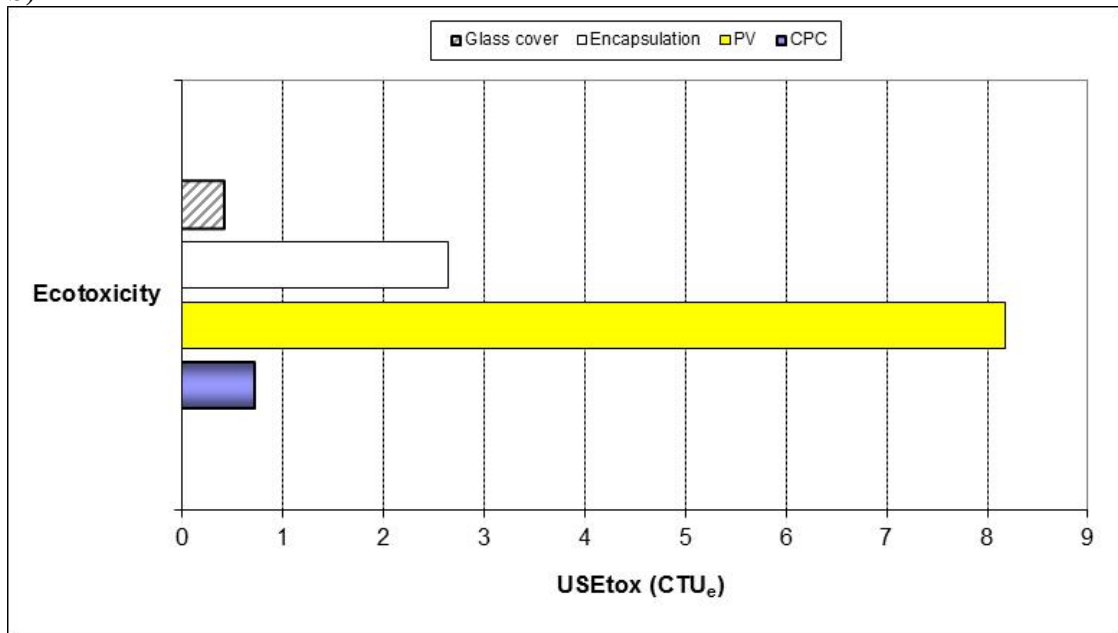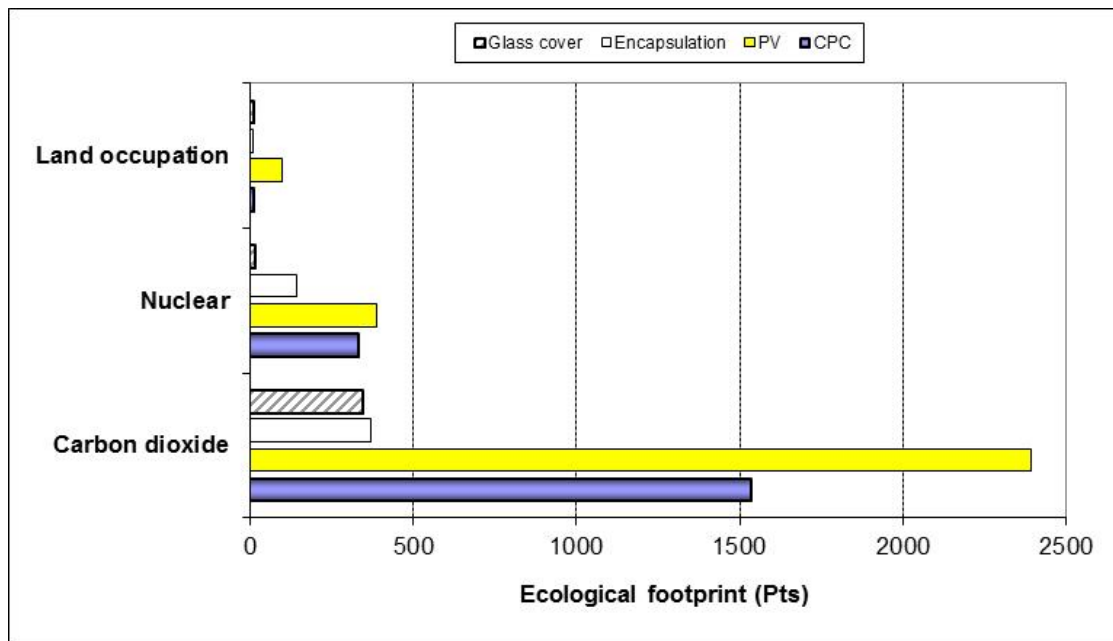
a)



b)



**Figure 3.** The contribution of each material/component to the total impact of CPV material manufacturing (43 modules; configuration with reflective film) based on USEtox/characterization in: a) $CTU_h$ and b) $CTU_e$.

**Figure 4.** The contribution of each material/component to the total impact of CPV material manufacturing (43 modules; configuration with reflective film) based on ecological footprint/single-score (Pts).
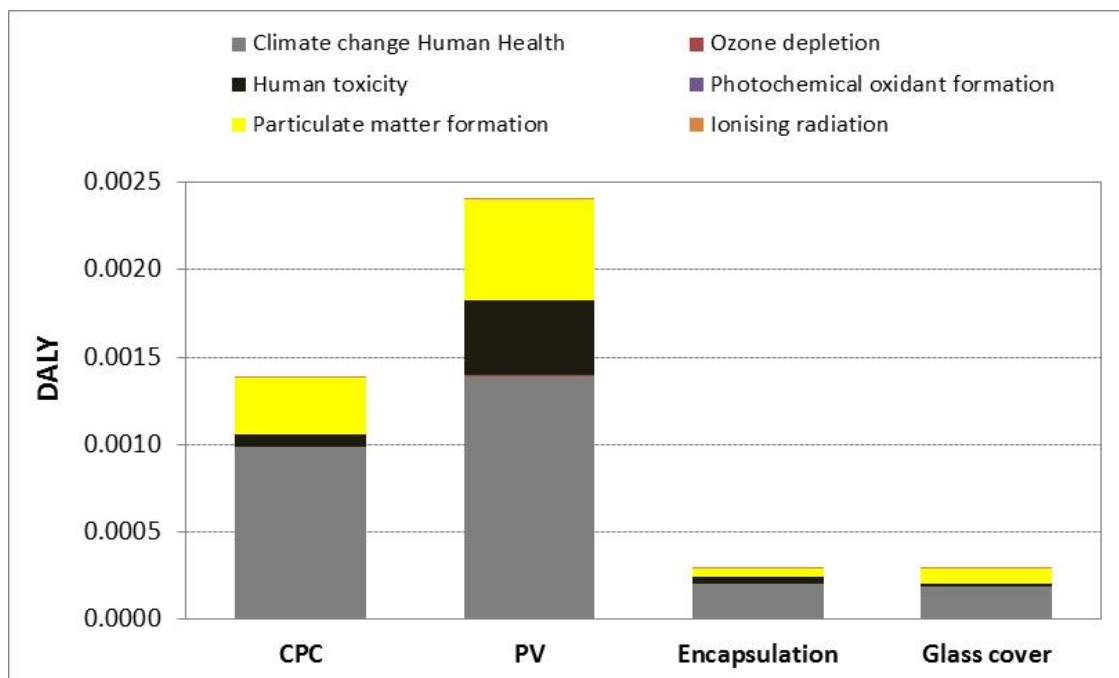


**Figure 5.** The contribution of each material/component to the total impact of CPV material manufacturing (43 modules; configuration with reflective film) based on ReCiPe/endpoint with characterization for the impact categories climate change/human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation (DALY).

**3.2. ReCiPe and EI99 payback times**

In Fig. 6 and Fig. 7, the results about the PBTs are presented. Among the studied cities, Barcelona shows the lowest ReCiPe and EI99 PBT values, ranging from 3.6 to 5.8 years, depending on the scenario. In addition, Exeter and Dublin show ReCiPe and EI99 PBTs varying from 3.7 to 7.8 years.

From Fig. 6 and Fig. 7, it can be observed that for the ReCiPe-based PBTs the differences between Barcelona and the other two cities are less than 0.3 years. This is mainly related with the calculation of the avoided impact due to the use of electricity from the proposed CPV instead of using electricity from the national grid ($I_{out.a}$) (Eq. 1). Certainly, for Barcelona this avoided footprint is higher than for Dublin and Exeter (since PV output (Table 1) and irradiance (Fig. 7) is considerably higher for Barcelona in comparison to the other two cities). Nevertheless, when PV outputs are converted into avoided impact based on the coefficients of the electricity mix of each country, the differences between $I_{out.a}$ of Barcelona and those of Exeter and Dublin are reduced (taking into account that the impact points per MJ delivered electricity are lower for the electricity mix of Spain than for the other two countries). At this point it should be noted that these calculations have some limits. In the frame of this concept, several perspectives can be adopted in order to improve the presented findings, e.g. modelling the electricity system to identify which type of production is avoided when PV electricity is produced.

On the other hand, for the EI99-based PBTs (Fig. 6 and Fig. 7) the differences between Barcelona and the other two cities range from around 1 to 2 years, a fact that is mainly associated with the calculation of $I_{out.a}$ based on EI99. As it was previously explained in section 3.1, the differences between the two LCIA methods (Goedkoop et al., 2009) are related with differences in the calculated environmental indicators.
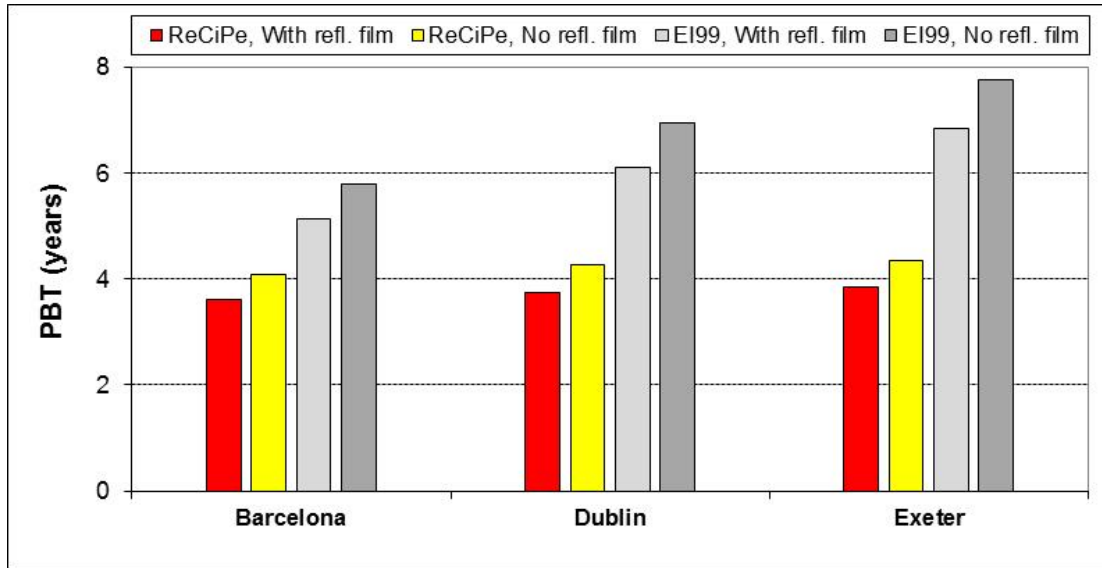
**Figure 6.** ReCiPe and EI99 PBTs for the CPV systems with and without reflective film, for Barcelona, Dublin and Exeter.

In addition, based on the findings illustrated in Fig. 6 and Fig. 7, the benefits from the utilization of reflective film can be seen: there is a reduction of ReCiPe and EI99 PBTs ranging from 0.5 to 0.9 years. At this point it should be noted that according to authors´ previous LCA (Lamnatou et al., 2015), the utilization of reflective film results in a reduction of around 11-12% in energy PBT and greenhouse-gas PBT.
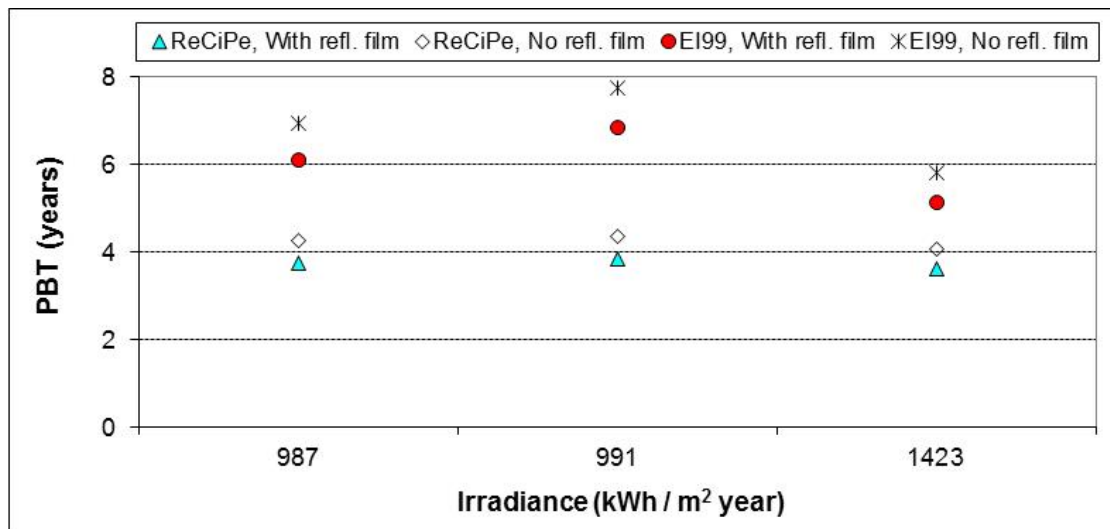


**Figure 7.** PBT in years (based on ReCiPe and EI99) vs. irradiance (kWh/m$^2$year) which receives the CPV surface. Irradiances 987, 991 and 1423 kWh/m$^2$year refer to Dublin, Exeter and Barcelona, respectively.

### 3.3. Avoided impact during use phase of the proposed BICPV

The avoided impact represents the benefits from the utilisation of the electricity produced by the BICPV with reflective film (during use phase of the system) instead of using electricity from national grid. In the following subsections, results (on annual and lifetime basis), based on the electricity of Spain, UK and Ireland are presented.

### 3.3.1. Annually avoided impact

In Fig. 8(a) and 8(b), ReCiPe/single-score and EI99/single-score results are illustrated and it can be observed that in general, for both methods the scores show similar tendency. More analytically, ReCiPe and EI99 reveal that human health is the category with the highest footprint savings, followed by resources. Moreover, ecosystems and ecosystem quality are the categories with the minimum avoided impact. Regarding the total scores (annual savings; system with reflective film), Barcelona shows 81 ReCiPe Pts and 78 EI99 Pts, Dublin has 78 ReCiPe Pts and 67 EI99 Pts, Exeter presents 76 ReCiPe Pts and 60 EI99 Pts. Thus, Barcelona presents higher avoided impact than the other two cities and the differences between the studied cities are more pronounced for the EI99 case (Fig. 8b) for the reasons that were previously explained (sections 3.1 and 3.2).
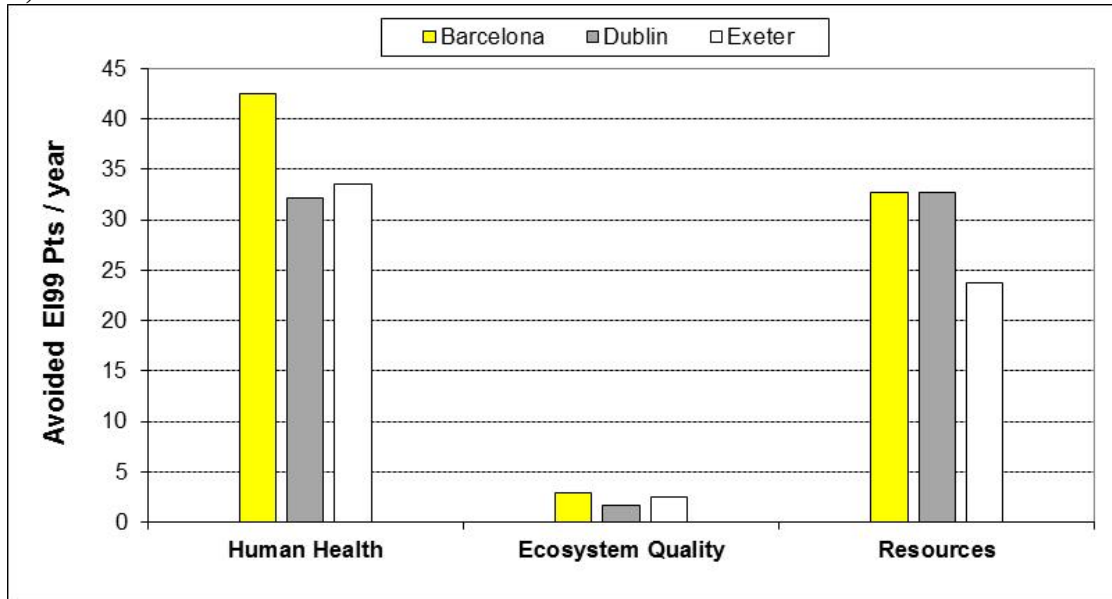
**a)**
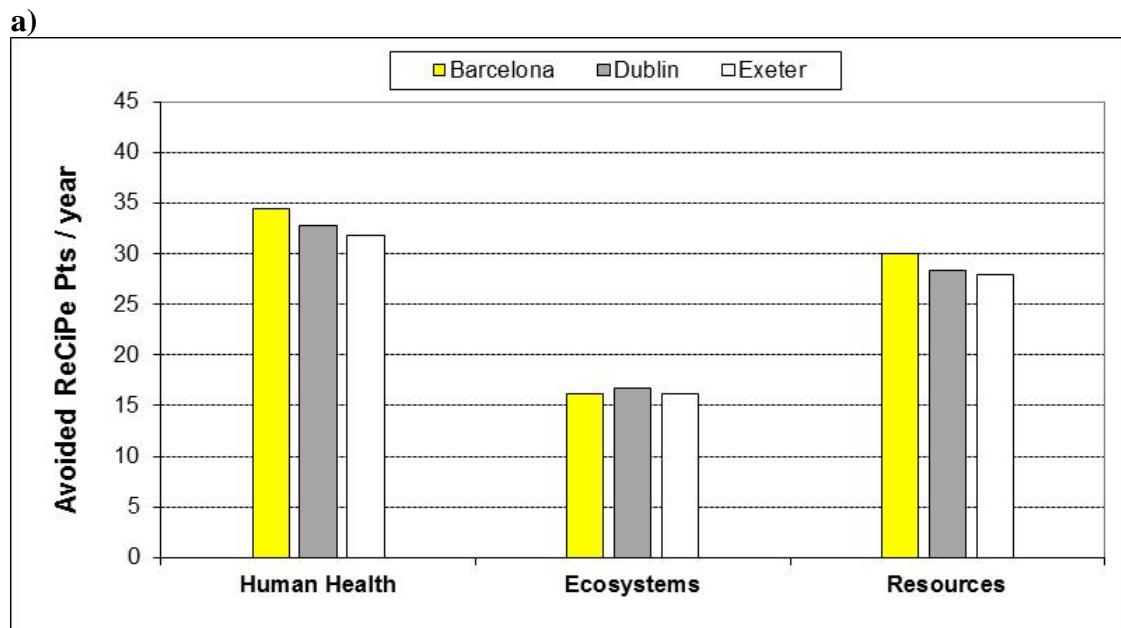
**b)**



**Figure 8.** Avoided impact (Pts per year), for the CPV with reflective film, for Barcelona, Dublin and Exeter, based on: a) ReCiPe/single-score and b) EI99/single-score.

### 3.3.2. Lifetime avoided impact

For the lifespan calculations, ReCiPe/single-score is adopted, based on three scenarios: 20, 25 and 30 years system lifetime. The results are presented in Fig. 9 and it can be observed that Barcelona achieves the maximum footprint savings (1581-2304 ReCiPe Pts) followed by Dublin (1527-2225 ReCiPe Pts), while Exeter shows the lowest avoided impact (1490-2172 ReCiPe Pts). On the other hand, by focusing on system lifespan, it can be seen that the adoption of 30-years (instead of 20-years) leads to 31.4% increase of the avoided impact.
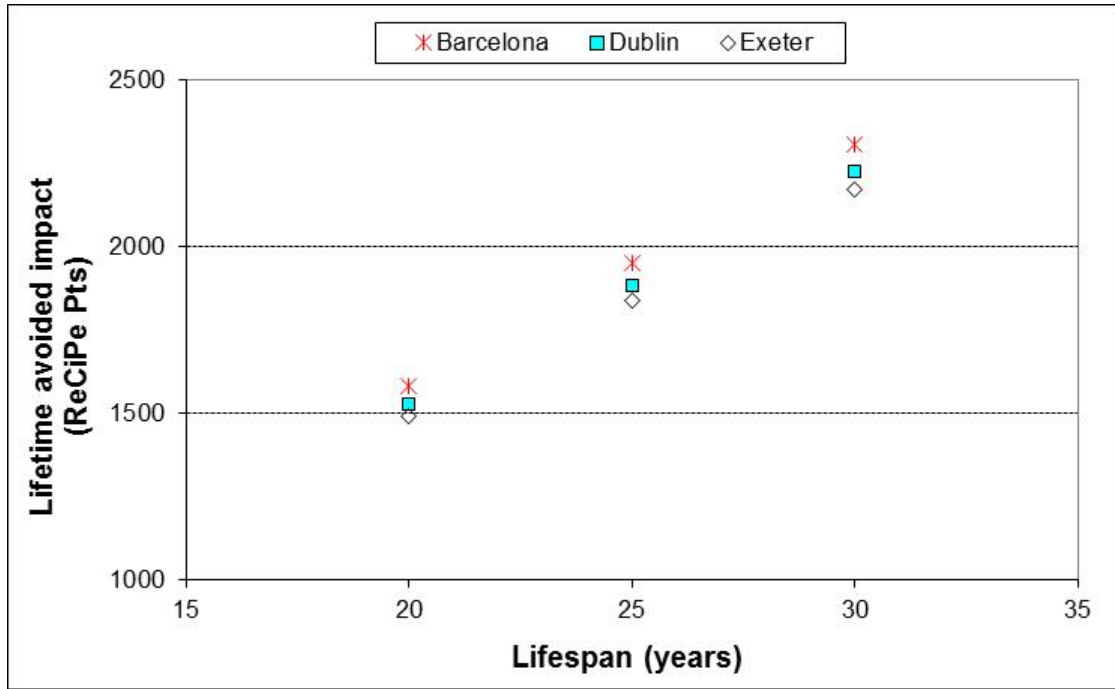
**Figure 9.** Avoided impact on a lifetime basis, based on ReCiPe/single-score (Pts), for the CPV with reflective film, for Barcelona, Dublin and Exeter. Scenarios: 20, 25 and 30 years lifespan.

### 3.4. Life-cycle impact based on ReCiPe/endpoint with characterization

The life-cycle footprint of the proposed system is also evaluated in terms of DALY and (species.yr). The calculations of DALY and (species.yr) impact per kWh of produced electricity have been conducted by taking into account the life-cycle footprint of the systems (with and without reflective film) and the CPV output (for each of the studied cities) on a 25-years basis (realistic scenario).

In Fig. 10, the life-cycle DALY footprint is illustrated for the category of climate change/human health (Fig. 10a) and for the categories of ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation (the last five categories are presented in Fig. 10b as «other categories»). From Fig. 10 it can be seen that the impact regarding climate change/human health (Fig. 10a) is higher than the impact regarding the other categories (Fig. 10b). Moreover, Fig. 10 demonstrates that, among the stages of life-cycle which are examined, material/module manufacturing is the stage with the highest footprint for all the studied categories (showing percentages 67-68% of the total life-cycle impact). Moreover, Fig. 10 reveals

that the phase with the second highest impact is use phase (with contributions 22-28% in the total life-cycle footprint).

On the other hand, in Fig. 11, DALY impact (ReCiPe/endpoint with characterization) per kWh of produced electricity (realistic scenario of 25-years lifespan), for several impact categories, is illustrated. From Fig. 11, it can be observed that, among the studied cities, Barcelona shows the lowest footprint. For example, for climate change/human health and for the CPV with reflective film, Barcelona presents $1.2 \times 10^{-7}$ DALY/kWh while the other cities have a footprint of around $1.8 \times 10^{-7}$ DALY/kWh. With respect to all the studied impact categories, climate change/human health has higher impact in comparison to the total impact of the other categories (ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation). Regarding the CPV configurations, Fig. 11 reveals that the utilization of reflective film improves the eco-profile of the reference system (configuration without reflective film): for example for Barcelona the use of reflective film results in a reduction of about $1.5 \times 10^{-8}$ DALY/kWh (in terms of climate change/human health). In general, for all the studied cities (Fig. 11), the differences between the configuration with and without reflective film are more pronounced for the category climate change/human health.
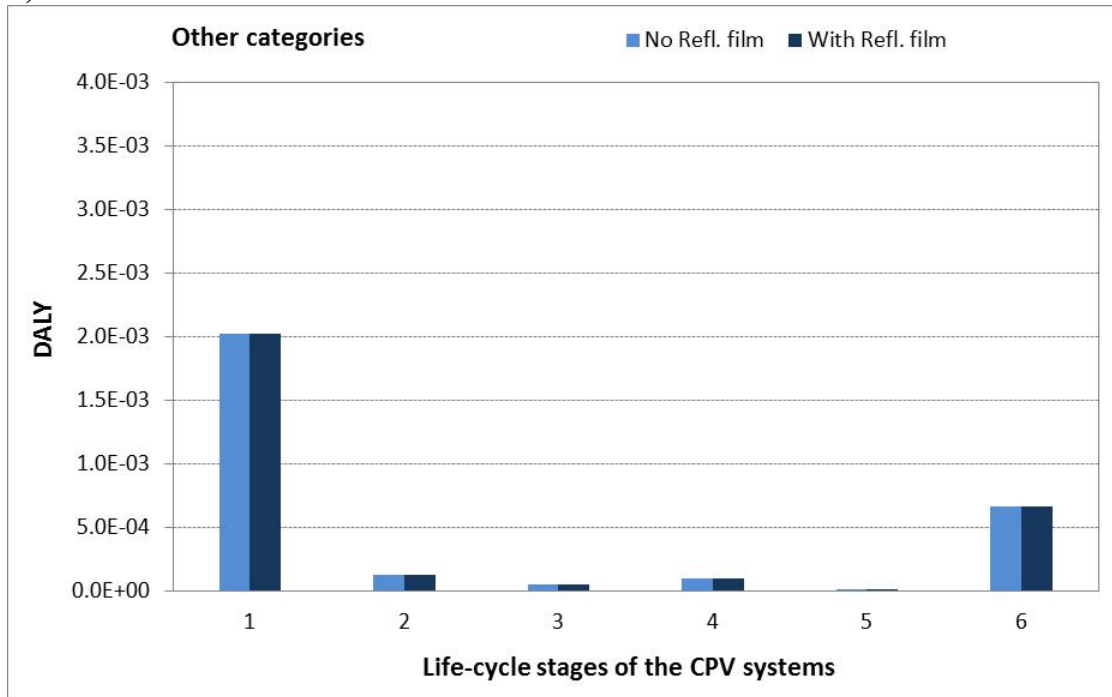
a)
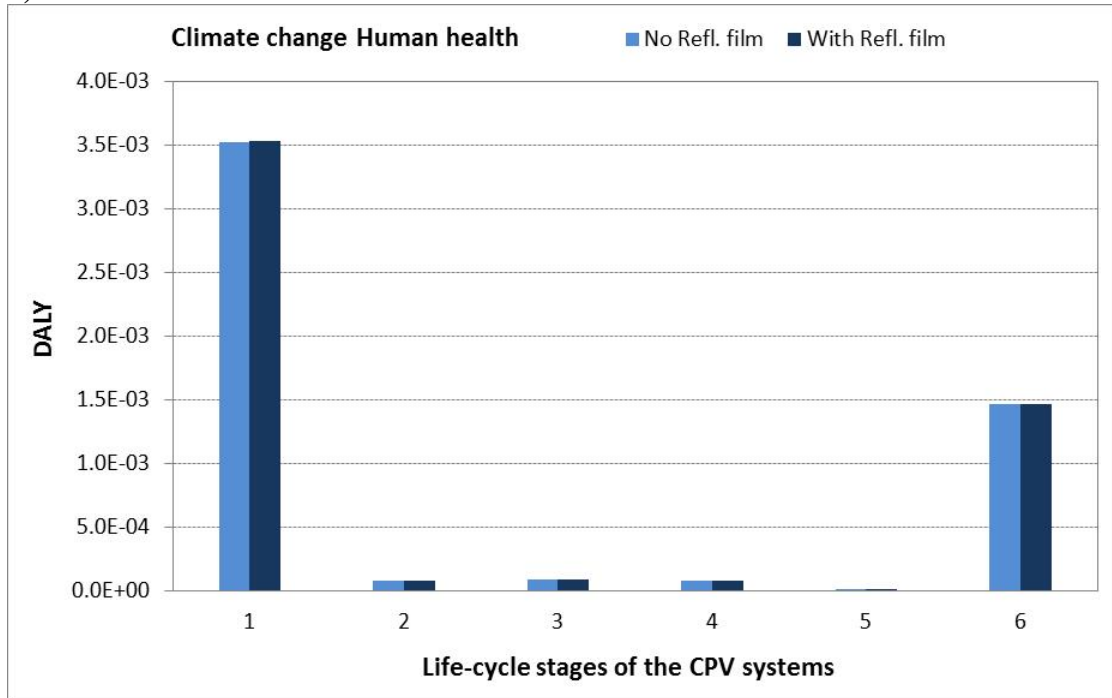


b)



**Figure 10.** Impact in DALY (ReCiPe/endpoint with characterization) for the life-cycle stages of: 1) material/module manufacturing, 2) material manufacturing of the additional components, 3) system installation, 4) disposal, 5) transportation and 6) use phase (lifespan). CPV systems with and without reflective film. Studied categories: a) climate change/human health and b) other categories (ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation).

In Fig. 12, the findings regarding climate change/ecosystems ((species.yr) per kWh of produced electricity) for the system without reflective film (Fig. 12a) and for the system with reflective film (Fig. 12b) are illustrated. Fig. 12 verifies the improved environmental performance (in terms of (species.yr)) of the CPV system for the case of Barcelona (in comparison to the cities from Ireland and UK). For example, for the configuration with reflective film and for climate change/ecosystems, the difference between Barcelona and Dublin is $3.2 \times 10^{-10}$ (species.yr)/kWh. In addition, Fig. 12 demonstrates the ecological benefits from the adoption of reflective film: there is a reduction in (species.yr)/kWh ranging from $8.4 \times 10^{-11}$ to $1.3 \times 10^{-10}$, depending on the scenario.
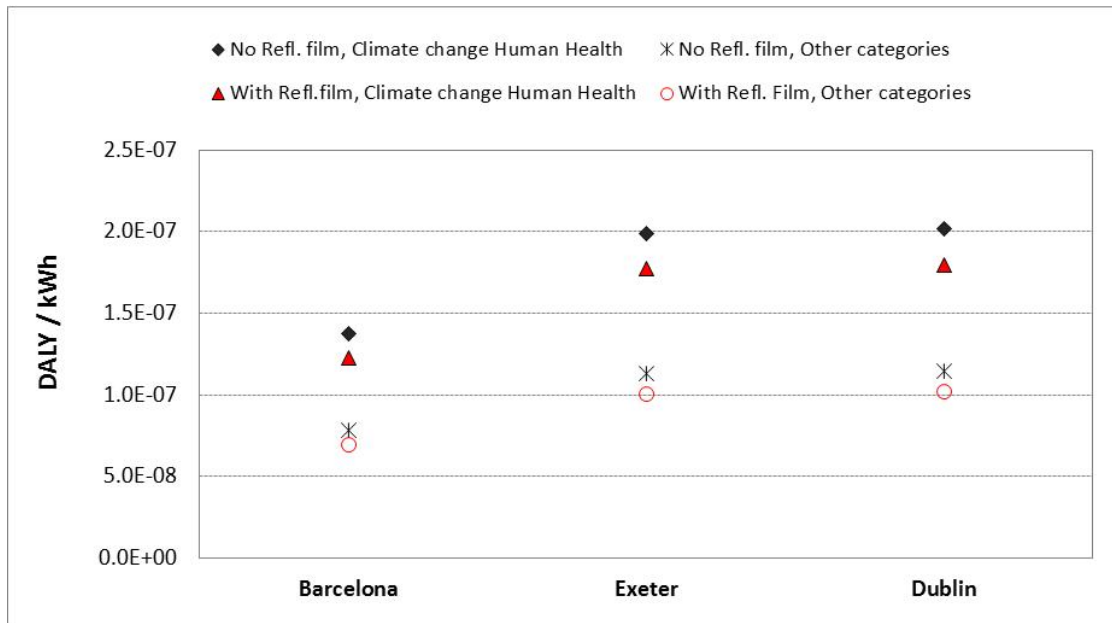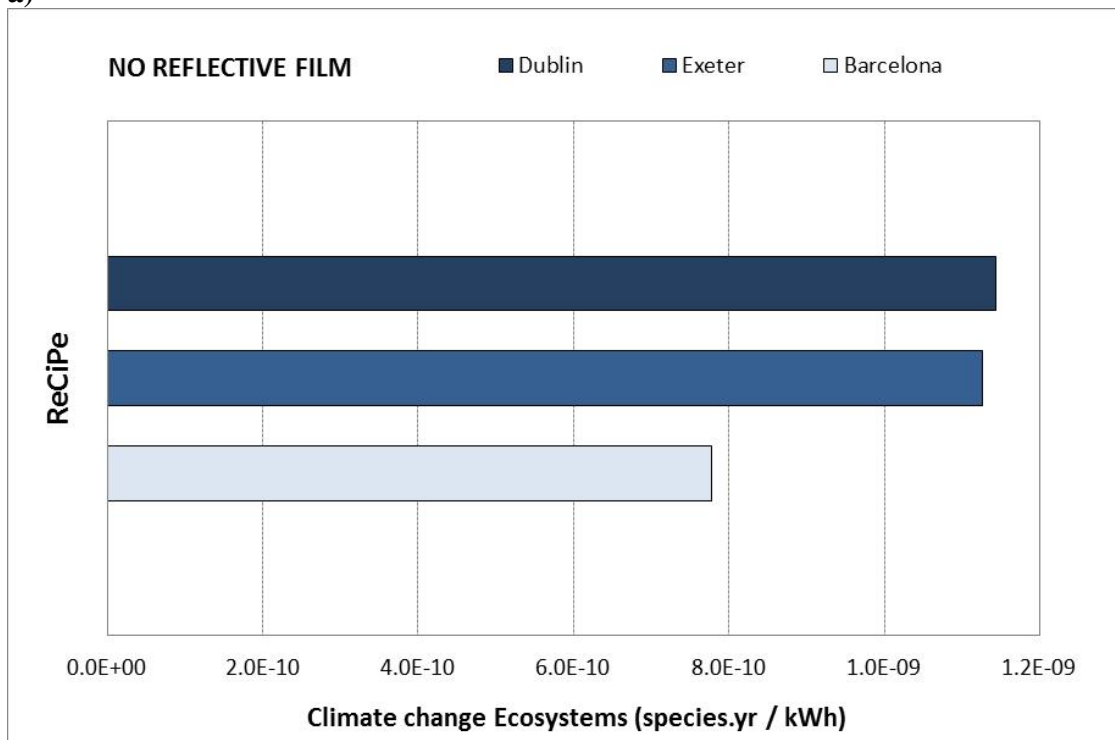


**Figure 11.** Impact in DALY (ReCiPe/endpoint with characterization) per kWh of produced electricity for Barcelona, Exeter and Dublin. CPV systems with/without reflective film and for 25-years lifespan. Studied categories: a) climate change/human health and b) other categories (ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation).
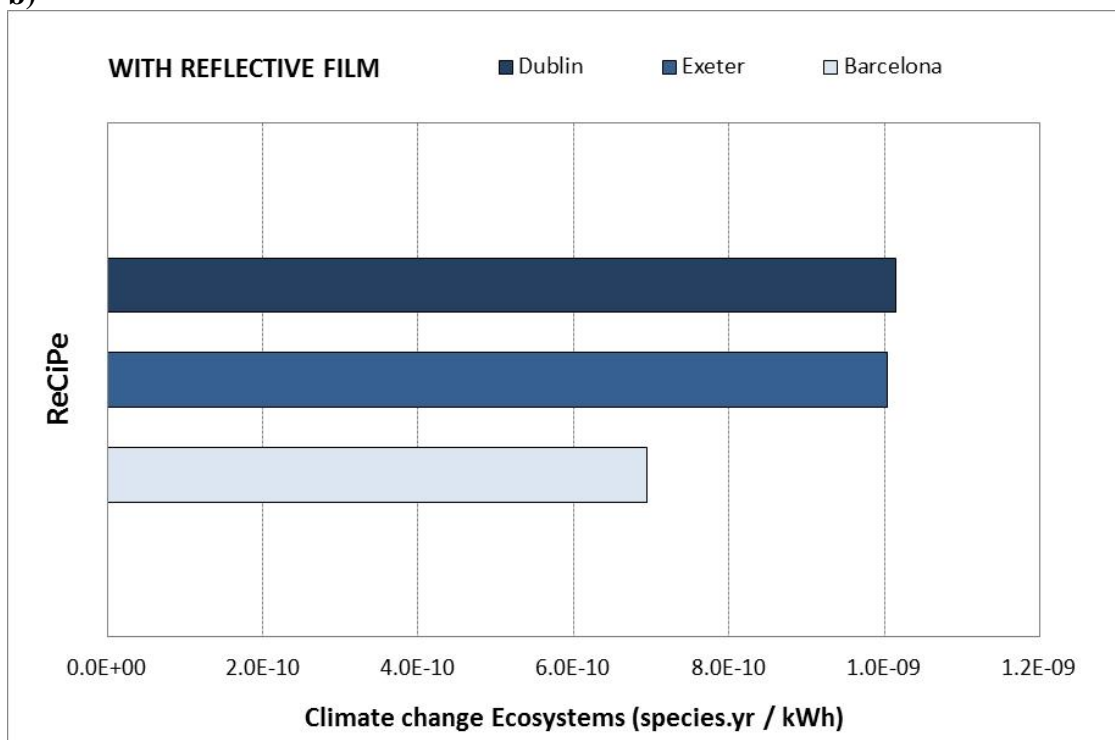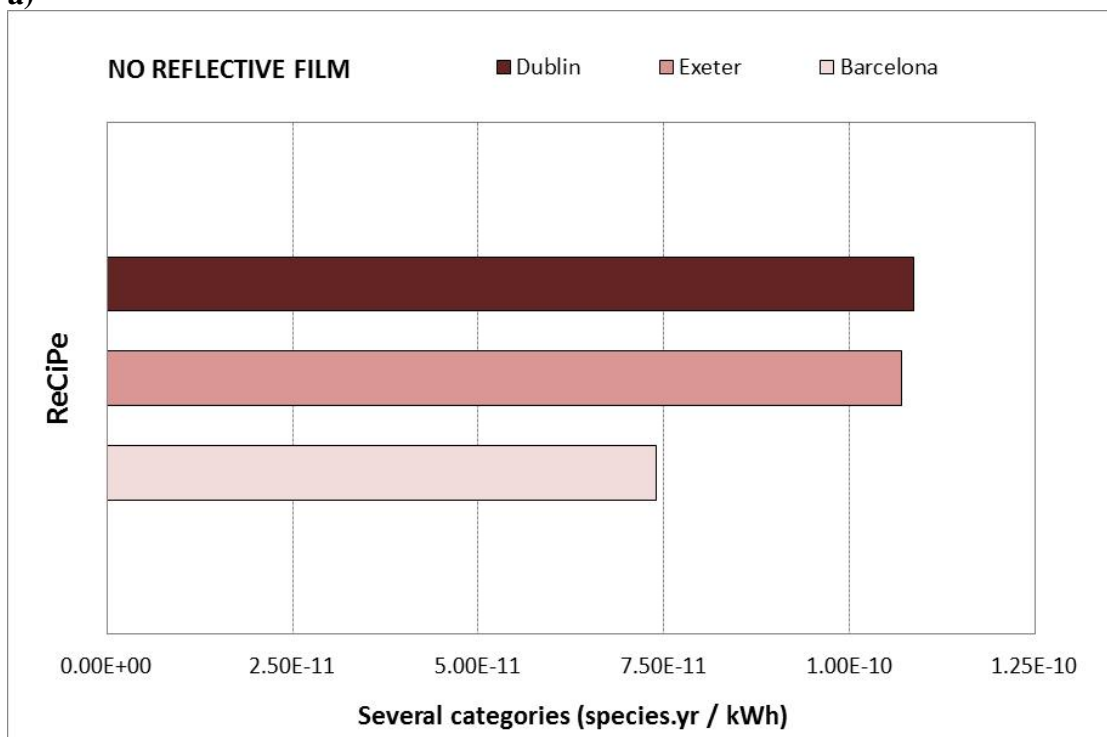
**a)**



**b)**



**Figure 12.** Impact (ReCiPe/endpoint with characterization) in (species.yr) per kWh of produced electricity for Dublin, Exeter and Barcelona. CPV system: a) without reflective film and b) with reflective film. 25-years lifespan. Studied category: climate change/ecosystems.

In Fig. 13, the impact (ReCiPe/endpoint with characterization) in terms of (species.yr) per kWh of produced electricity, based on different impact categories (terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation and natural land transformation: presented in Fig. 13 as «several categories»), for the CPV system without reflective film (Fig. 13a) and for the CPV system with reflective film (Fig. 13b), is illustrated. From Fig. 13 it can be seen that, among the studied cities, Barcelona shows the lowest footprint and Dublin shows the highest impact. More specifically, for the CPV with reflective film, the difference between Barcelona and Dublin is $3.0 \times 10^{-11}$ (species.yr)/kWh. Furthermore, Fig. 13 verifies the advantages of using reflective film: there is an impact reduction ranging from $8.1 \times 10^{-12}$ to $1.2 \times 10^{-11}$ (species.yr)/kWh.

Finally, by comparing Fig. 12 and Fig. 13 it can be observed that the impact in (species.year)/kWh based on climate change/ecosystems (Fig. 12) is higher than the one based on the total impact of the categories presented in Fig. 13 as «several categories».

a)



b)
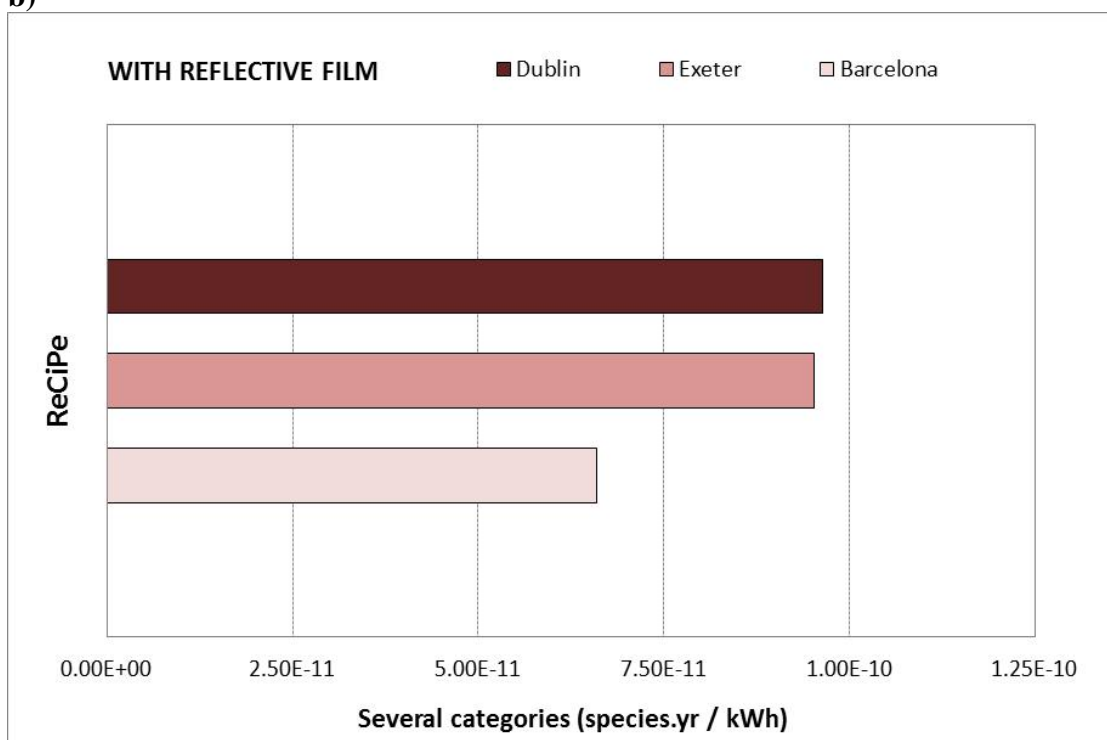


**Figure 13.** Impact (ReCiPe/endpoint with characterization) in (species.yr) per kWh of produced electricity for Dublin, Exeter and Barcelona. CPV system: a) without reflective film and b) with reflective film. 25-years lifespan. Several categories (total impact): terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation and natural land transformation.

### 3.5. $R_{x.EI99}$ factor, $R_{x.ReCiPe}$ factor and EI99/ReCiPe ratio

The $R_x$ ratio is a potential conversion factor between EI99 (or ReCiPe for the present study) (Pts) and EF results ($m^2a$). If the ratio is approximately equal for all the studied products, this implies that the two methods do not differ in their gross ranking of the products (Huijbregts et al., 2008).

In the frame of the present study, $R_{x.EI99}$ and $R_{x.ReCiPe}$ are evaluated based on Eq. (2) and (3), respectively. The results, by taking into account the impact for manufacturing of the 43 modules and the additional system components (for both configurations: with/without reflective film), reveal that $R_{x.EI99}$ and $R_{x.ReCiPe}$ are about 26.2 and 28 $m^2a$/Pts, respectively. These factors, based on life-cycle calculations, are 21.3 and 27.4 $m^2a$/Pts, for EI99 and ReCiPe, respectively. Huijbregts et al. (2008) calculated $R_{x.EI99}$ for 19 homogeneous product/process subgroups (containing in total 1549 processes) and it was found that the majority of the products have $R_{x.EI99}$ around 30 $m^2a$/Pts $\pm$ a factor of 5. Thus, the results of the present work are close to the values proposed by Huijbregts et al. (2008).

Finally, the ratio EI99/ReCiPe (single-score, Pts) has been also evaluated. By taking into account material manufacturing phase (for modules and additional system components; configuration with reflective film) this ratio is 1.06.

### 3.6. Results from the literature

A direct comparison with literature studies is not possible since there are differences e.g. in terms of the studied PV technologies. However, in this section some findings of the present investigation are presented along with results from the literature, showing that, in general, there is quite good agreement:

- Based on ReCiPe, Mohr et al. (2013) calculated an overall damage score of 0.01 ecopoints/kWh for a multi-Si PV system. The life-cycle results of the present BICPV system (with reflective film; realistic scenario of 25-years lifetime) show 0.009 ReCiPe

Pts/kWh for Barcelona (close to the findings of Mohr et al., 2013) while for Exeter and Dublin this value is 0.013 ReCiPe Pts/kWh.

- Menoufi et al. (2013), based on material manufacturing phase and EI99 method, found a footprint of approximately 160 EI99 Pts for a BICPV (two CPV modules of 250 $W_p$ each; single-crystalline Si PV cells; reflectors as window blinds). In the present investigation, by taking into account material manufacturing (for modules and additional system components) and module manufacturing of the proposed BICPV with reflective film, the impact is 278 EI99 Pts. Thus, by assuming a system of 0.5 $kW_p$ (instead of 1 $kW_p$) the impact is expected to be approximately 139 EI99 Pts (thereby, quite close to the results of Menoufi et al., 2013).

- Jungbluth et al. (2005) evaluated PBTs for several configurations of 3-$kW_p$ slanted-roof PV (mono-crystalline and poly-crystalline Si cells) systems in relation to a modern natural gas-fired, gas combined cycle power plant. The EI99 PBT values varied from approximately 5 to 7 years. For the present BICPV system, for Barcelona, Dublin and Exeter (system with and without reflective film) EI99 PBTs range from 5.1 to 7.8 years (thus, quite similar to the range of Jungbluth et al., 2005).

- Hirschberg et al. (2014) presented ReCiPe/endpoint impact (Hierarchist, Europe H/A), in DALY/kWh, from operation of electricity production. For the case of PV crystal (Switzerland) a footprint of about $1.9 \times 10^{-7}$ DALY/kWh was shown. From this impact approximately half was in terms of climate change/human health and half it was for human toxicity, ionizing radiation, photochemical oxidant formation and particulate matter formation (Hirschberg et al., 2014). For the above mentioned five impact categories, the present BICPV (with reflective film and 25-years lifespan) for the case of Barcelona shows a footprint of $1.92 \times 10^{-7}$ DALY/kWh; thereby, close to the findings of Hirschberg et al. (2014).

### 3.7. Uncertainty, sensitivity analysis and future prospects of the present study

The results of an LCA can be influenced by several sources of uncertainty (adopted assumptions and LCIA methods, quality of the data, etc.). Certainly, the experts should estimate the extent of the sources of uncertainty so as to improve the reliability of the obtained eco-profiles (Cellura et al., 2011). In the frame of this concept, sensitivity and uncertainty analysis can be conducted in the frame of LCA studies in order, for example, to test the adopted assumptions and the data used, to identify key parameters affecting the impact of a component, to determine which materials require accurate data, etc. (Source: Sensitivity and Uncertainty).

Taking into account the above mentioned issues and the findings of the present study which reveal (according to different methods) that PV laminates have a considerable contribution to the total impact of the proposed system (material manufacturing phase), an extension of the present work could include a sensitivity analysis for PV impact based on different sources of data/databases. Given the technological developments, for example within the field of crystalline Si PV modules, which verify that there is a considerable potential to reduce the environmental impact of crystalline Si PVs while reducing the production costs (Mann et al., 2014), such analysis (sensitivity for PV cell impact) could provide a wider view of the issues studied in the frame of the present work, identifying key parameters related with the eco-profile of the proposed BICPV system.

On the other hand, another source of uncertainty is associated with the electricity mixes. A discussion about this has been presented in the assumptions.

Finally, it should be noted that other sources of uncertainty can be related with the resource indicator (e.g. depending on the reserve option of the adopted LCIA

method) and/or with health and ecosystem indicators (e.g. depending on how radioactivity and nuclear risk[6] are accounted for in these indicators).

## 4. CONCLUSIONS

In continuation to authors´ previous LCA about the evaluation of the environmental profile of a linear dielectric-based BICPV by means of embodied energy and embodied carbon, the present work based on different methods/indicators offers a much deeper analysis and additional results about the environmental performance of the above mentioned system, according to multiple LCIA methods and environmental indicators: ReCiPe (single-score as well as with characterization), EI99, EF, USEtox, ReCiPe-based and EI99-based PBTs, ReCiPe impact in DALY and (species.yr) per kWh, etc. Two BICPV configurations (without reflective film (reference system) and with reflective film) are investigated, for different cities (Barcelona, Exeter and Dublin).

With respect to the phase of material manufacturing (43 modules; CPV with reflective film), in general, ReCiPe results (single-score) are in accordance with EI99 findings (single-score). Based on both methods, the component with the maximum contribution to the footprint regarding resources is CPC while for ecosystems/ecosystem quality and human health PVs have the highest contribution. Concerning USEtox results (with characterization; for human toxicity/cancer, human toxicity/non-cancer and ecotoxicity), PVs have the highest footprint. Regarding EF (single-score results), the category of carbon dioxide shows remarkably higher impact comparing to the other two categories (land occupation and nuclear). Moreover, based on EF results, PVs and CPC are the components with the highest footprint.

Concerning PBTs, taking into account both configurations with/without reflective film, Barcelona presents the lowest ReCiPe and EI99 PBTs ranging from 3.6

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[6] Nuclear plants are often old and the risks may have a small probability to occur but they have very large effects. In addition, another environmental issue is related to the management of the nuclear waste.

to 5.8 years. On the other hand, Exeter and Dublin show PBTs varying from 3.7 to 7.8 years.

According to ReCiPe/endpoint results with characterization and for the impact category climate change/human health (CPV with reflective film), Barcelona shows $1.2{\times}10^{-7}$ DALY/kWh while Dublin and Exeter present a footprint of about $1.8{\times}10^{-7}$ DALY/kWh.

In terms of the annual savings during use phase of the system with reflective film (benefit due to the use of the electricity produced by the CPV instead of utilising electricity from the national grid), ReCiPe and EI99 results, in general, show similar tendency for the cases which are examined. Among the studied cities, Barcelona shows the highest savings: ranging from 1581 to 2304 ReCiPe Pts (depending on the scenario in terms of system lifespan).

Regarding the two CPV configurations, the findings based on multiple approaches demonstrate that reflective film remarkably improves the ecological profile of the reference system (configuration without reflective film), verifying the results of the authors´ previous LCA about the proposed BICPV system based on energy PBT and greenhouse-gas PBT.

Finally, several environmental indicators of the proposed CPV are calculated and presented along with data from the literature. It can be seen that, in general, there is quite good accordance between the present findings and those of the literature, taking into account that a direct comparison is not possible. This is because there are differences between the present study and those of the literature (in terms of the adopted technologies, etc.).

Conclusively, the present investigation provides useful information about the environmental profile of a CPV system appropriate for BI applications, verifying its

ecological benefits for building and environment and based on multiple LCIA methods and life-cycle environmental indicators shows how small modifications (with small input in material for the reflective film) of the reference system (configuration without reflective film) can remarkably improve the eco-profile of the proposed system in practice and over its use phase. On the other hand, the proposed LCA model can also be applied to similar systems providing useful information about their environmental performance and allowing comparisons, from ecological point of view, between similar configurations over their life-cycle, showing the best option in the frame of clean production technologies.

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