Building-integrated photovoltaic/thermal (BIPVT) prototype: Environmental assessment focusing on material manufacturing

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Abstract: The study presents environmental issues about a building-integrated photovoltaic/thermal (BIPVT) configuration. The studied module is a prototype that has been developed at the Ulster University (Belfast, UK) and it has been patented. The investigation gives emphasis on the phase of material manufacturing and it includes the inputs in terms of the materials/components needed for one module. For the evaluation of the BIPVT prototype from environmental point of view, a model has been developed based on different methods: CED (cumulative energy demand), GWP (global warming potential: $CO_{2.eq}$ emissions), ReCiPe, etc. A comparison with the literature is also provided and in general, a good agreement is observed. Conclusively, the present study provides useful information given the fact that in the literature there are few studies which present environmental issues/LCA (life cycle assessment) about BIPVT and most of them show results in terms of embodied energy and $CO_{2.eq}$ emissions.

1. Introduction

Photovoltaic/thermal (PVT) systems combine PV modules with thermal units and they offer conversion of the solar radiation into electricity and heat as well as higher energy output than the standard PV modules (which provide only electricity). PVT systems can be classified based on different criteria: working fluid (PVT/air, PVT/water, etc.), type of circulation (natural or forced) of the working fluid (Tripanagnostopoulos et al., 2005), type of integration into the building, etc. Regarding the last criterion, there is the specific case of PVT that are integrated into the building (BIPVT: building-integrated PVT), offering multiple advantages (higher aesthetic value, etc.) in comparison to the solar systems which are BA (building-added) (Lamnatou et al., 2015; Lamnatou and Chemisana, 2016). In the literature there are some studies which present environmental issues/LCA (life cycle assessment) for BIPVT: Agrawal and Tiwari (2015), Crawford et al. (2006), Kamthania and Tiwari (2014), Battisti and Corrado (2005), Rajoria et al. (2013; 2016), Chow and Ji (2012), Sun (2014). The results reveal that from energetic and from environmental point of view, PVs are more interesting when the PV module is utilized as dual-output. By taking into account that: 1) BIPVT offer multiple advantages, 2) there are few investigations about BIPVT environmental profile and most of these present CO_2 emissions and EPBT (Lamnatou and Chemisana, 2016), it can be seen that there is a need for more investigations about BIPVT LCA/environmental issues. In this way, the present article presents the environmental profile of a patented BIPVT prototype, according to different methods.

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2. Materials and methods

The phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation are adopted (ISO 14040:2006, ISO 14044:2006). The functional unit is one PVT module (electricity production: 112 W; thermal production 400 W; PV-cell surface: 0.56 m^2; thermal-absorber surface: 1 m^2). For the calculations of the impact, the phase of material manufacturing is considered, for one PVT module.

The PVT module is patented (Smyth, 2013) and it has been developed at the Ulster University, in UK. A full size prototype PVT module was fabricated and assembled for experimental evaluation. Fig. 1 details the prototype unit complete with PV module. The unit is based on a patented thermal diode Integrated Collector Storage (ICS) vessel designed with an elliptical (Egyptian eye) profile, with dimensions 1m x 1m and 150 mm deep, to provide an inherent structural strength to withstand the forces put upon the vessel under evacuation. The vessel was made from an external 1.2 mm thick SS 304 outer vessel supported by an internal exo-skeleton. The inner (thermal storage) vessel was of a similar elliptical profile with a volume of 35.1 litres under no vacuum and of 35.65 litres when under vacuum. A value of 30 litres per m^2 is deemed suitable for ICS type solar water heaters by much of the published literature. The PVT module is encased in a weather tight enclosure. The sides and back are made from white acrylic capped ABS and along with a 50 mm thick insulating layer, form the outer unit casing. The aperture front is made from clear (UV treated) PETG which is a suitable transparent aperture material. The PVT is a modular façade-integrated solar collector designed to: 1) reduce heat loss in cool climate conditions and reduce cooling loads in warm climate conditions by adding an additional insulating element to the building fabric, 2) provide an energy saving by augmenting the thermal energy and power requirement of the building by direct on site generation, 3) integrate renewable energy technology to comply with current building regulations and reduces carbon footprint. The multi-functionality of the unit provides a unique product concept. The unit is predominately seen to be a modular system for use in façade-mounted applications (note: an inclined version is being developed). The unit can be used across a range of building structure typologies, replacing envelope elements for both new-build domestic and commercial buildings.

Fig. 1. The studied BIPVT module.

For the study, SimaPro 8 and ecoinvent database have been utilized. In Table 1, details about the components/materials/masses for one PVT module are presented.

Table 1. Life Cycle Inventory (LCI): components/materials/masses for one PVT module.

Components/materials	**Mass (kg per module)**
PV cells (mono-crystalline)	1.70
Outer vessel (steel)	21.09
Inner vessel (steel)	12.64
Casing (ABS: acrylonitrile butadiene styrene)	4.94
Aperture casing (PETG: polyethylene terephthalate glycol)	3.05
Insulation (polystyrene)	2.12
Brackets (steel)	1.41
Pipework (HDPE: high density polyethylene)	0.52
Pipework (steel)	0.36
Fittings (steel)	0.25
Cables (PVC (polyvinyl chloride), copper)	0.10
Bonding paste (polymer)	0.10
Gaskets (silicone)	0.10
Bolts (steel)	0.05
Screws (brass)	0.02

The following methods (SimaPro 8, ecoinvent database) were utilized in order to assess the environmental profile of the proposed PVT module: 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 (single-score), 4) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (with characterization), 5) ReCiPe Midpoint (H) V1.10 / Europe Recipe H (with characterization), 6) Ecological footprint V1.01 / Ecological footprint (single-score), 7) Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A (single-score), 8) USEtox (default) V1.03 / Europe 2004 (with characterization). Details about the above mentioned methods can be found in the report (PRé, 2014).

3. Results and interpretation

3.1. Phase of material manufacturing: one PVT module

In Fig. 2 the contribution of each component/material to the total CED of one PVT module is presented. From Fig. 2 it can be seen that PV, outer vessel and inner vessel are the components with the highest CED, showing values from 676 to 1986 MJ_{prim}. All the other components (except of the three above mentioned) present a total CED of 1128 MJ_{prim}, with casing (ABS) contributing to 43% of this value (followed by aperture casing (PETG) and insulation (polystyrene) with percentages 20-21%).

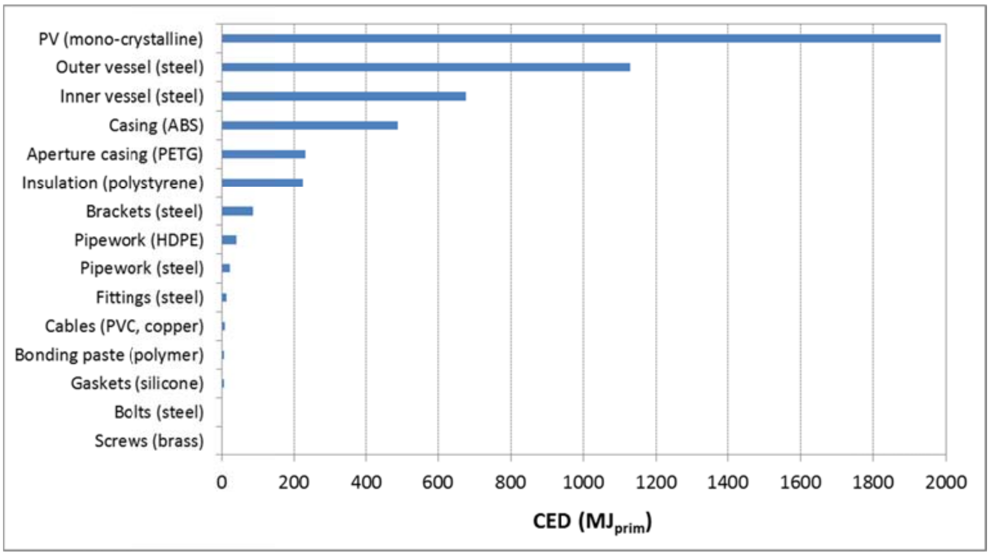


Fig. 2. Contribution of each component/material to the total CED of one PVT module.

Fig. 3 illustrates the contribution of each component/material to the total GWP 100a of one PVT module. From Fig. 3 it can be observed that also based on GWP 100a, PV, outer vessel and inner vessel present the highest values, ranging from 52 to 146 kg $CO_{2.eq}$. The above mentioned three components are followed by casing (ABS) which shows 23 kg $CO_{2.eq}$. All the other components contribute to the total GWP 100a with values less than 10 kg $CO_{2.eq}$.

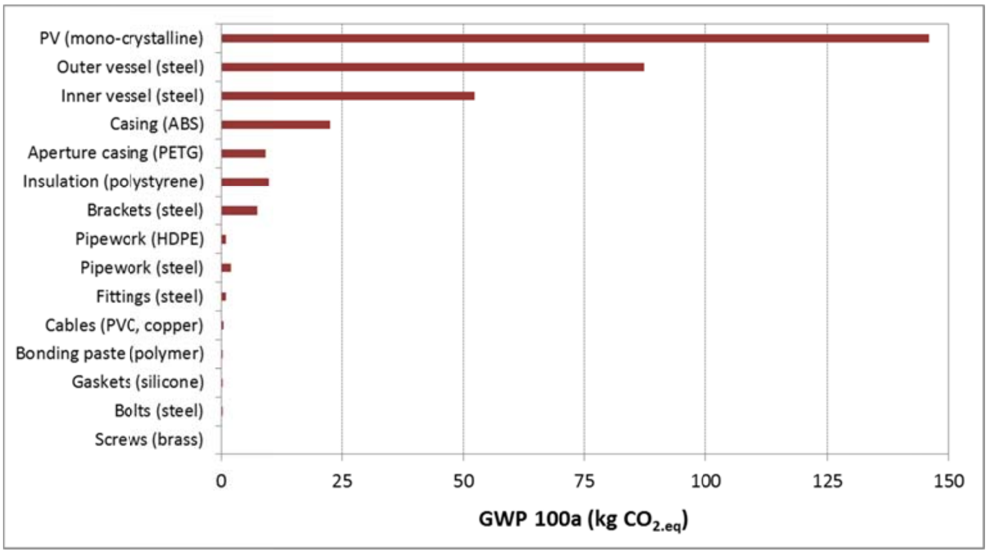


Fig. 3. Contribution of each component/material to the total GWP 100a of one PVT module.

Moreover, in Fig. 4 the contribution of each component/material to the total impact of one PVT module according to ReCiPe endpoint single-score (including all the endpoint categories (Human health, Ecosystems and Resources)). Fig. 4 shows that PV, outer vessel and inner vessel present the highest values, ranging from 14 to 23 Pts. More specifically, PV and inner vessel show around 14-15 Pts while outer vessel shows 23 Pts. All the other components (except of the three above mentioned) present values less than 3 Pts.

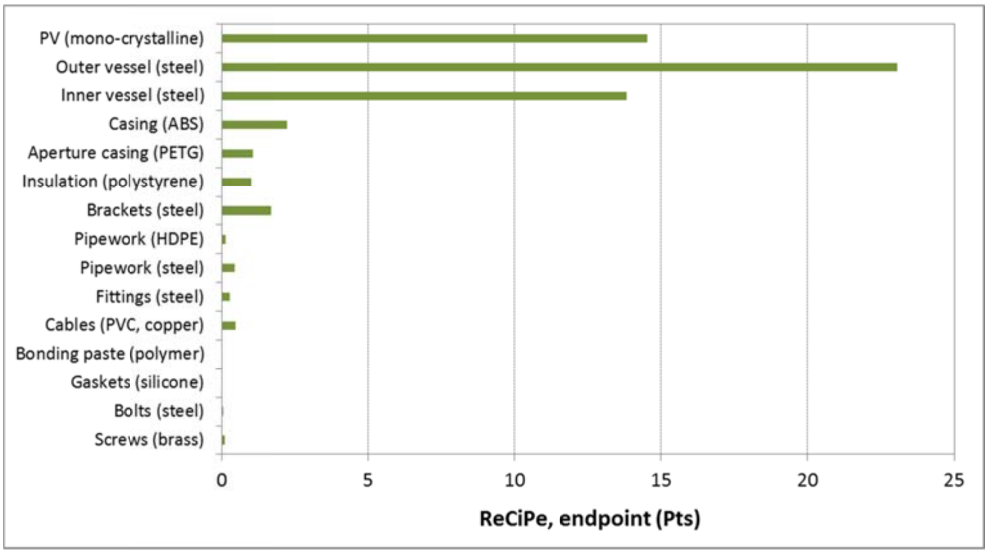


Fig. 4. Contribution of each component/material to the total ReCiPe Pts (ReCiPe endpoint, single-score, including all the endpoint categories (Human health, Ecosystems and Resources)) of one PVT module.

Except of the above presented results (Fig. 2-4), the environmental profile of the proposed PVT module has been also assessed based on additional methods. In Table 2, the contribution of the components to the total impact of one PVT module is given, according to these additional methods. PV, outer vessel and inner vessel are presented separately since they are the components with the maximum contribution. The percentage for all the other components (casing, aperture casing, insulation, brackets, pipework, fittings, cables, bonding paste, gaskets, bolts and screws) is presented as a total value. From Table 2, it can be seen that:

1) For most of the cases, PV cells show percentages higher than outer vessel, inner vessel and the other components (more specifically, PV cells present 37-43% contribution based on CED, GWP (20a, 100a, 500a), ReCiPe endpoint with characterization (DALY; species.yr), EF single-score (carbon dioxide) while according to USEtox the contributions are 86% and 55% (for human toxicity non-cancer and ecotoxicity, respectively)).

2) Outer vessel is the component with the second highest impact, showing for three cases percentages higher than the PV cells (more analytically, based on ReCiPe endpoint single-score, EI99 single-score and USEtox human toxicity cancer, the outer vessel has contributions 14%, 22% and 10% higher than the PV cells).

3) Inner vessel is the component with the third highest impact, presenting percentages 3-17% lower than those of the outer vessel.

4) The other components (which are presented in Table 2 as a total value), based on most methods, show contributions close to those of the inner vessel.

Table 2. Contribution of the components to the total impact of one PVT module. The impact for casing, aperture casing, insulation, brackets, pipework, fittings, cables, bonding paste, gaskets, bolts and screws, is presented as a sum (other components).

Methods	PV cells (%)	Outer vessel (%)	Inner vessel (%)	Other components (%)
CED	40	23	14	23
GWP 20a	42	25	15	18
GWP 100a	43	26	15	16
GWP 500a	43	26	16	15
ReCiPe endpoint single-score (Pts)	25	39	23	13
ReCiPe endpoint with characterization (DALY)	37	31	19	13
ReCiPe endpoint with characterization (species.yr)	43	26	16	14
EF single-score (Pts): carbon dioxide	43	26	16	15
EI99 single-score (Pts)	20	42	25	13
USEtox, human toxicity cancer (CTU_h)	29	39	23	9
USEtox, human toxicity non-cancer (CTU_h)	86	7	4	2
USEtox, ecotoxicity (CTU_e)	55	22	13	10

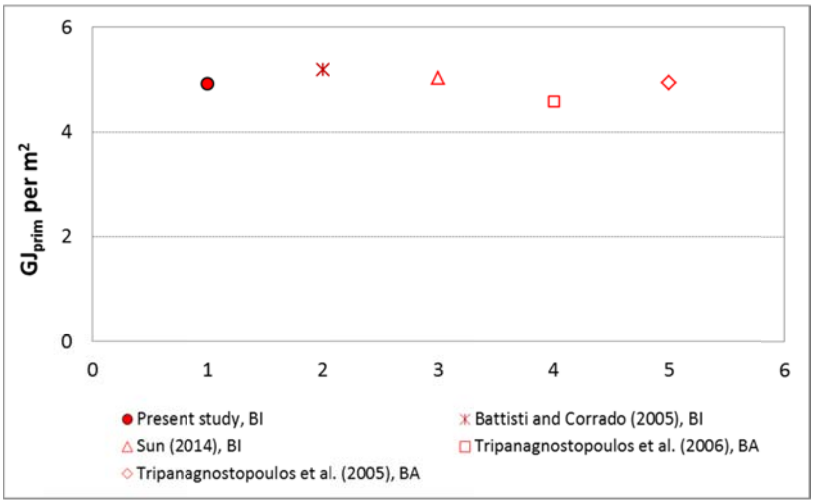
4. Issues which influence PVT profile from environmental point of view

There are different factors which affect the environmental profile of a BIPVT system: PV cell material, the total mass of aluminium components (since aluminium production is energy intensive), the use of alternative materials (e.g. polymeric), the lifespan of the adopted materials/components, the use of recycling, the type of building integration and the heat transfer fluid (Lamnatou and Chemisana, 2016). By taking into account the above mentioned factors, it can be seen that the environmental profile of the proposed BIPVT module can be improved for example by the utilization of less aluminium (or use of alternative materials with lower impact) since the vessels (inner and outer) show a considerable impact as well as by the adoption of recycling for certain materials.

5. Comparisons with the literature

The findings of the present study (based on CED and GWP 100a) have been compared with those of Battisti and Corrado (2005) (BIPVT, multi-crystalline Si), Sun (2014) (BIPVT, mono-Si) and Tripanagnostopoulos et al. (2005; 2006) (BA PVT, multi-crystalline Si). The results of the above mentioned studies have been elaborated in order to evaluate the expected embodied energy and GWP per m^2 of module. In Fig. 5(a) and 5(b) these comparisons are illustrated and it can be seen that, in general, there is a good agreement. In addition, it can be noted that most of the cases present around 5 GJ_{prim} and 0.4 t $CO_{2.eq}$ per m^2 of PVT module (BI or BA).

a)



b)

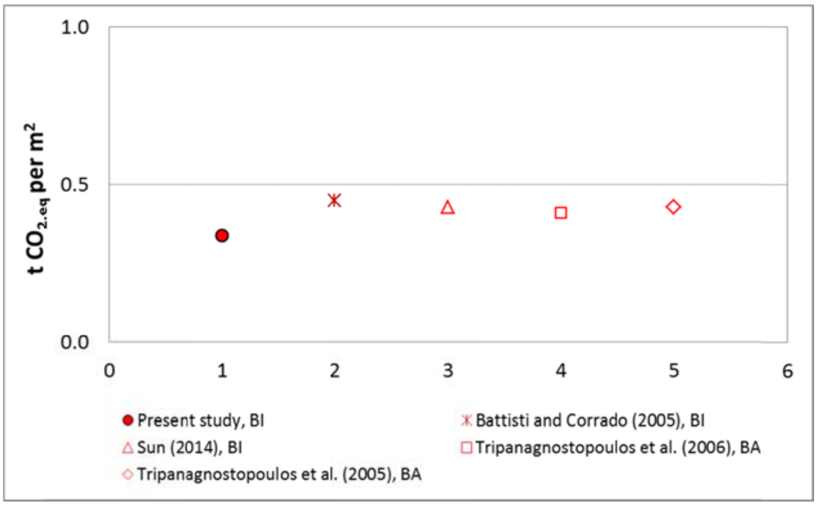


Fig. 5. Comparisons in terms of: a) GJ_{prim} and b) t $CO_{2.eq}$ per m^2 of PVT module.

6. Conclusions

For the studied BIPVT, the results reveal that PV cells, outer vessel and inner vessel are the components with the highest impact, based on all the adopted methods. More specifically, the above mentioned three components show: 1) CED values from 676 to 1986 MJ_{prim}, 2) GWP 100a from 52 to 146 kg $CO_{2.eq}$, 3) 14-23 ReCiPe Pts (endpoint, single-score including the three endpoint categories Human health, Ecosystems and Resources). Issues which influence the environmental profile of the proposed PVT are also included and critically discussed. Moreover, a comparison with the literature is provided and in general, a good agreement is observed.

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