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Life cycle energy analysis and embodied carbon of a linear dielectric-based concentrating photovoltaic appropriate for building-integrated applications

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ABSTRACT

Life-cycle analysis of a Concentrating Photovoltaic (CPV) for building-integrated applications is conducted. Two configurations (with and without reflective film) are examined: based on embodied energy/embodied carbon, multiple scenarios and databases. Several environmental indicators are calculated for Exeter, Barcelona, Madrid, Dublin and Paris. Among the studied cities, considering both configurations, Greenhouse-gas Payback Time (GPBT) has the highest values for Paris (27.2–33.1 years) and the lowest values for Dublin (3.3–4 years). Regarding Energy Payback Time (EPBT) (average based on two databases; CPV with reflective film), Barcelona and Madrid show the minimum values (about 2.4 years) while Paris, Exeter and Dublin show EPBTs 3.2–3.5 years. Reflective film results in 0.2% increase in system initial footprint (embodied energy and embodied carbon; material manufacturing of the modules) while on a long-term basis, this additional impact is compensated (since the CPV with reflective film has higher electrical output). By using the reflective film there is a reduction of about 11–12% in EPBT and GPBT, depending on the scenario. The energy return on the investment is also evaluated, showing the highest values for Madrid and Barcelona among the studied cities. Moreover, EPBT is calculated with an alternative way by considering replacement of the materials of a wall.

1. Introduction

For Building-Integrated (BI) applications, Concentrating Photovoltaic (CPV) systems can provide several advantages in comparison to the conventional flat-plate PVs. In the review study of Chemisana [1], a comparative analysis of the main CPV systems in terms of their suitability for use in buildings was presented. CPV technology offers higher electrical conversion efficiency in the PV cells, better use of space, ease of recycling of the constituent materials and reduced use of toxic products related to the manufacture of the PV cells. Nevertheless, BICPV systems viability dependents on factors such as their ability to offer economic advantages over flat-plate PV technologies and their Concentration Ratio (CR), taking into account that for BI applications are of particular interest CPV systems with low CR (less than 10×) (this is because they provide benefits, for instance no need for tracking) [1].

In the literature, there are experimental and modelling-based investigations about CPV systems appropriateness for BI applications. In the following paragraphs some of these studies are presented.

Baig et al. [2] modelled and analysed the performance of a dielectric-based linear CPV system by using ray tracing and finite element method. The results were compared with experiments. A linear asymmetric Compound Parabolic Concentrator (CPC) with a geometrical CR of 2.8× was evaluated. The initial experiments showed a maximum power ratio of 2.2 compared to a non-concentrating counterpart. Moreover, an increase of 16% in the average power output was achieved by utilizing a configuration with reflective film.

Zacharopoulos et al. [3] conducted a three-dimensional optical analysis of two dielectric, non-imaging concentrating covers for BIPVs. The results revealed that an asymmetric concentrator is more suitable for use at building façades. For a wide range of solar incidence angles, the optical efficiencies were over 90% for both concentrators. The optimum collection tilt angle (for two different latitudes) and the monthly and annual collected solar energy for both concentrators were predicted and compared to flat-plate PV covers (of the same PV and aperture area). Adopting high-transmittance materials for dielectric concentrating covers enables such refractive systems to achieve high solar energy acceptance;

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thus, less PV material is required and the initial capital cost is reduced.

Mallick et al. [4] investigated non-concentrating and asymmetric BI (façade-integrated) PVs with CPC, based on an experimental comparison. Different numbers of PV strings connected within the system were evaluated and a power ratio of 1.62 measured compared to a similar non-concentrating PV panel with the same cell area. The results demonstrated that the use of a 50° acceptance angle asymmetric compound parabolic PV concentrator increased the maximum power point by 62% (the power ratio was 1.62) for a geometrical CR of 2.0 with the same incident solar radiation compared to a similar non-concentrating PV.

On the other hand, in the literature there are several studies about the evaluation of PV environmental profile by means of Life Cycle Analysis (LCA). Several types of PV technologies/systems have been studied. In the following paragraphs, some of these investigations are presented.

Fthenakis et al. [5] conducted a study about methodology guidelines on PV LCA. Guidance on PV-specific parameters used as inputs in LCA and on choices and assumptions regarding Life Cycle Inventory (LCI) data analysis and on the implementation of modelling approaches, was presented [5]. Raugei et al. [6] investigated, by means of LCA, advanced PV modules: CdTe and CIS compared to poly-Si. Alsema and Nieuwlaar (year of the study: 2000) [7] evaluated the energy viability of PV systems. For multi-crystalline silicon and thin-film amorphous silicon, by assuming 1700 kWh/m^{2}year irradiation, the Energy Payback Time (EPBT) was found to be 2.5–3 years for roof-top installations while it was almost 4 years for multi-megawatt, ground-mounted systems. Moreover, de Wild-Scholten and Schottler [8] studied thin-film modules-production processes and their environmental assessment. Gaiddon and Jedliczka [9] compared environmental indicators of PV electricity in several cities (of Spain, UK, etc.). In the literature, there is also a study about the energetic and environmental impact of roof-mounted PVs for several PV cell technologies and different Italian cities [10]. In terms of LCA about PV-green roofs, the investigation of Lamnatou and Chemisana [11] revealed that a PV-green roof can compensate its additional environmental impact and on a long-term basis it can be proved to be more environmentally friendly than a PV-gravel or a PV-bitumen roof (due to PV-green higher production of electricity).

On the other hand, there are some LCA studies about small-scale CPVT (concentrating photovoltaic/thermal) configurations. A point-focus CPVT for domestic use was evaluated and it was found that the CO_2 avoided (in a year) was equal to 3376 kg [12]. A low-concentrating PVT system installed on the roof of a building at University of Palermo (Italy) was also studied [13]. An EPBT value of 0.7 years was found while the global-warming-potential PBT was calculated to be 1 year [13].

Regarding LCA studies about BIPV and BICPV systems, Seng et al. [14] conducted an economic, environmental and technical analysis of BIPVs in Malaysia. Hammond et al. [15] presented a whole systems appraisal of UK BIPV. Perez et al. [16] conducted a study about façade BIPVs and determined functional relationships between environmental impacts of façade BIPV under a range of incident radiation and under a range of applications (in terms of the types of façades the BIPV replaces). Menoufi et al. [17] performed an LCA of a BICPV (material manufacturing phase). A BICPV scheme (with reflectors, two CPV modules of 250 W_p each and single-crystalline silicon PV cells) was compared with a BIPV scheme (of the same power and with mono-crystalline PV cells). The results showed that by installing the BIPV scheme instead of the BICPV one, there was an increase of the total environmental impact (this increase was around 13.5% according to EI99 methodology and 10% according to EPS 2000 methodology). In a recent review article about LCA of solar technologies, Lamnatou et al. [18] showcased the scarcity of case studies on LCA of BI solar thermal, BIPV, BIPVT and BICPV systems.

Concerning LCA studies about BI active solar thermal systems, Lamnatou et al. [19] investigated a BI solar thermal collector, based on embodied energy and embodied carbon methodologies. Three configurations were studied (with the collectors in series or parallel connection and the tubes at the same level or at different levels). The results showed that the system with the collectors in parallel connection/tubes at different levels has an EPBT of around 0.5 years if recycling is adopted. In continuation of [19], Lamnatou et al. [20] conducted a study about the environmental performance of the BI solar thermal collectors studied in [19], based on multiple approaches and Life Cycle Impact Assessment (LCIA) methodologies (IMPACT 2002+, etc.). Several scenarios were examined and a critical comparison of the proposed systems with other types of solar thermal and conventional heating systems was also presented.

With respect to LCA of large-scale, high-concentration PV systems, the investigation of Fthenakis and Kim [21] reveals that although operating high-concentration PV configurations demands considerable maintenance, their life-cycle environmental burden is much lower than that of flat-plate c-Si systems operating in the same high-insolation regions. The EPBT of Amonix 7700 PV (high-concentrating modules; two-axis tracking; operation at Phoenix, AZ) which was studied by Fthenakis and Kim [21] was found to be 0.9 years and the emissions where calculated to be 27 g $CO_{2,eq}$/kWh over 30 years. Moreover, Nishimura et al. [22] conducted a study about a high-concentration PV power generation system. Two hypothetical case studies in Toyohashi, Japan and Gobi desert in China were examined in order to investigate the influence of installation location and PV type on environmental load and EPBT [22].

The literature review reveals that most of the PV LCA studies are about simple (without concentration) PV systems. Regarding the integration of the PVs into the building, most of the LCA investigations regard building-added configurations. Moreover, there are few LCA works about CPV. Thus, there is a gap in the literature within the field of LCA about BICPV systems. The present investigation aims at filling the above mentioned gap by studying the environmental performance of a linear dielectric-based PV system of low concentration, appropriate for BI applications, based on Embodied Energy (EE) and Embodied Carbon (EC), multiple scenarios (different countries/cities, etc.) and databases. Several environmental indicators are calculated, presented along with data from the literature and critically discussed. The information is provided separated into sections/subsections regarding: EE and EC of material manufacturing phase, avoided carbon emissions during use phase (having as reference the electricity mixes of several countries), carbon emissions per kWh of produced electricity of the proposed CPV system, payback times and Energy Return on the Investment (EROI).

2. Materials and methods

The implementation of the LCA is conducted according to ISO 14040:2006 [23] and ISO 14044:2006 [24]. The phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation, are adopted.

2.1. Definition of the functional unit and system boundaries

The functional unit of 1 kW_p is used. For the production of 1 kW_p, a system with 43 modules (3.86 m^2 net PV surface; 10.53 m^2 aperture area) is needed. The following phases are taken into account: material manufacture (for the modules and system additional