Challenges and research needs in life cycle analysis of building-integrated photovoltaic

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Challenges and research needs in life cycle analysis of building-integrated photovoltaic

Xiaoyu Yan[1,2]
[1]Environment and Sustainability Institute, University of Exeter, Penryn, UK
[2]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn, UK

E-mail: xiaoyu.yan@exeter.ac.uk

Abstract. Building-integrated photovoltaic (BIPV) is a promising solar energy technology that looks set to grow in popularity in the pursuit of a sustainable future. It has the potential to mitigate some of the main concerns over ground-mounted solar energy systems such as land use. However, there is an apparent gap in our understanding of its life cycle environmental impacts. Very few life cycle analysis (LCA) studies have evaluated BIPV comprehensively in comparison with standalone PV systems and other energy technologies. In this paper, we review the limited existing LCA studies on BIPV and identify the challenges and future research needs. The findings will help researchers, industries and policy makers better understand the environmental sustainability of BIPV to facilitate its development.

Keywords: solar energy; building-integrated photovoltaic; life cycle analysis; environmental sustainability

1. Introduction

Building-integrated photovoltaics (BIPV) is an emerging renewable energy technology that has great potential for meeting a significant portion of the electricity needs of cities globally [1,2]. It also has the potential to mitigate some of the main concerns over ground-mounted solar energy systems such as land use, which may result in competition with food production or ecological impacts. However, the overall environmental performance of BIPV is less well understood compared with standalone solar farms or building-applied photovoltaics (BAPV) such as roof-mounted systems. Life cycle analysis (LCA) is a key tool to evaluate the environmental sustainability of any products or technologies and has been applied extensively in energy [3–5]. Here, we review the limited existing LCA studies on BIPV and identify the challenges and further research needs in this area.

2. Review of the literature

The literature search using keywords including building integrated, solar energy, PV, environmental impacts and LCA resulted in more than 30 publications. There are studies investigating BI solar thermal energy systems (e.g., [6]) and solar PV and thermal (PVT) systems (e.g., [7]). These are excluded from the present review as PV only systems were analysed. Some of the studies investigated BAPV instead of BIPV and therefore are excluded as well.

Li et al. (2018) presented an LCA of a novel high optical performance low-concentration concentrator PV module for building south wall integration in China [8]. However, it is unclear whether the PV system evaluated was BIPV or BAPV as no details of the integration were given in the paper. In addition, there was no mentioning of the PV system replacing conventional building materials or influencing building energy performance.

Jayathissa et al. (2016) assessed a novel Adaptive Solar Façade based dynamic PV system in comparison with existing static PV systems [9]. Although the authors used BIPV to describe this technology in the paper, it is very difficult to justify that as the system was added to existing buildings.

Wang et al. (2016) performed a life cycle energy and GHG analysis of a 10 kW monocrystalline silicon based BIPV system as roof for a test building in Shanghai [10]. They found that the EPBT, GPBT and GHG footprint of the BIPV system are 3.1 years, 0.4 years and 60 gCO_2e/kWh, respectively. However, many methodological details are lacking in this study. For example, the goal and scope of the LCA were not clearly defined and the inventory data was not presented at all.

Lamnatou et al. (2016) reported an environmental assessment of a linear dielectric-based building-integrated concentrating PV (BICPV) system using several different LCIA methods including ReCiPe Endpoint, Eco-indicator 99, USEtox and Ecological footprint [11]. They found that reflective film considerably improves the eco-profile of the BICPV system and that material/module manufacturing is the stage with the highest impact for all the studied categories. However, the results were only presented using highly aggregated indicators. This made them difficult to be compared with those from most other studies.

Lamnatou et al. (2017) conducted a comprehensive LCA to evaluated the environmental performance of a dielectric-based 3D BICPV device [12]. Several scenarios and life-cycle impact assessment (LCIA) methods including Cumulative Energy Demand (CED), IPCC 2013 GWP, ReCiPe Endpoint, Ecological footprint, USEtox and Eco-indicator are adopted to calculate environmental performance for six different cities: Barcelona, Seville, Paris, Marseille, London and Aberdeen based on simulated power generation. Most of the results were presented using highly aggregated indicators, making direct comparisons with other studies difficult. The GHG footprint was found to range from 105 (Barcelona) to 171 (Aberdeen) gCO_2e/kWh. The energy return on investment (EROI) varies from 5 to 18 for the different cities.

Kristjansdottir et al. (2016) presented a comparison of the life cycle GHG emissions from the PV systems in 3 different Zero Emission Buildings (ZEBs) in Norway [13]. The 3 ZEBs had different types and configuration of PV systems: 1) Poly-Si BAPV mounted on top of the roof; 2) Mono-Si BIPV fully integrated as roof; and 3) Poly-Si PV semi-integrated into the roof with the mounting structure replacing normal roofing and the modules mounted on top of a solid board and able to be removed without any impact on the building physics. They found that under the baseline scenario, life cycle GHG emissions of electricity generated was 45, 80 and 85 gCO_2e/kWh for the BAPV, BIPV and semi-BIPV systems, respectively. The results also show that benefits from the reduction in demand for traditional roofing material are small (13 and 3 $kgCO_2e/m^2$ for BIPV and semi-BIPV systems, respectively) relative to the total emissions (350 and 280 $kgCO_2e/m^2$ for BIPV and semi-BIPV systems, respectively). Under the baseline scenario, the greenhouse gas payback time (GPBT) was found to be 3, 7 and 8 years for the BAPV, BIPV and semi-BIPV systems, respectively. However, the calculation of the GPBT numbers involved some projections of the emissions intensity of European grid electricity and is not very easy to interpret.

Belussi et al. (2015) assessed a BIPV ceramic tile prototype developed in a research project [14]. The system consists of a PV layer formed by a thin film of amorphous silicon deposited on a ceramic substrate and is intended for installation on ventilated facades. A entirely attributional LCA approach was adopted with a goal to evaluate the environmental impact of BIPV module production and identify the stages with the greatest impact. The system boundary was “cradle-to-gate” and the LCIA method used was CML2001 which included 12 impact categories. Primary data for the LCI was claimed to be collected through field interviews and questionnaires but key data such as the inventory of the materials used in the BIPV system was not presented. The results for the 3 cities in Italy simulated (Milan, Rome and Agrigento) show that the environmental impacts of the BIPV system are comparable to the conventional PV systems. In particular, the GWP and embodied energy of electricity produced from the BIPV system were found to be 27.8-38.4 gCO_2e/kWh and 0.49-0.68 MJ/kWh, respectively.

Ng and Mithraratne (2014) evaluated life cycle environmental performance of 6 different commercially available thin-film modules as semi-transparent BIPV windows under the tropical conditions of Singapore [15]. Previously performed energy simulations were adopted in the LCA. It

was found that the CED of the 6 systems varies from 240 to 2754 MJ/kWh, with the corresponding EPBT and EROI being 0.7-2 years and 12-35, respectively. The modules with the worst performances were mainly due to their low visible transmittances, energy efficiencies and higher thermal conductivities.

Menoufi et al. (2013) assessed a BICPV scheme assembled and tested on a small building model at the University of Lleida (Spain) in comparison to a hypothetical BIPV scheme. The scheme is to represent the installation of the reflectors as windows blinds. Two CPV modules of 250 Wp each are used as the receiver units. A hypothetical BIPV scheme mainly consisting of two transparent PV modules achieving the same power as the CPV ones is used as a comparison. The LCIA methods used include Eco-Indicator99 and EPS 2000. The results show that the environmental impact of BIPV scheme is 10%-14% higher than that of the BICPV scheme.

Hammond et al. (2012) performed energy analysis and LCA on modern BIPV roof tiles (mono-crystalline) connected in a modular arrangement. The study was completed with the assistance of a UK manufacturer and was used as a proxy for (domestic) BIPV products within the UK. The LCIA method chosen was Eco-indicator 99 and the LCA software SimaPro 7.1 was used to perform the calculations. The energy analysis revealed a short (displaced) energy payback period of 4.5 years for the system studied. The embodied energy and GHG emissions were found to be 83 GJ and 4500 $kgCO_2e$ for a 2.1 kWp mono-crystalline BIPV roof tile system (the functional unit chosen). This may be offset against the avoided impact of roof tiles, 217 $kgCO_2e$ and the avoided impact of 25 years of UK grid electricity, 26,700 $kgCO_2e$, resulting in a net saving of 22,400 $kgCO_2e$ over its lifetime.

3. Challenges and further research needs

During the review, many issues with existing LCAs on BIPV systems became apparent. For example, many studies actually evaluated BAPV even though the term BIPV was used [16–19]. There needs to be a clearer definition for these terminologies to reduce the ambiguity.

While some studies (e.g., [13]) follows the ISO guidelines for LCA and clearly presented the majority of the key information needed for readers to really understand the details of the study and findings, most studies fail to do so. Some studies only focused on limited energy or carbon/GHG indicators [15] whereas some studies look at many different impacts using various impact assessment methods [12].

In some studies there are many scenarios to explore the effects of many parameters such as location, system lifetime, with or without material replacement effects on the life cycle impacts [12]. While this is important (as it can offer insights into which parameters are key to the impacts), it makes comparisons across studies difficult. It would be beneficial to always use a baseline case and then vary different parameters to see the effects. This way the key results from the baseline case would be much clearer and easier to be compared with other studies. Different studies also use different functional units, system boundaries, data sources for key system parameters and inventory. More consistent approaches in these aspects and clearer presentation of these key information will help not only the readers of the individual papers but also researchers doing reviews and meta-analysis.

Another issue is that many studies mainly report results in figures without presenting all numerical values in the text (e.g., see [12]). This also makes it difficult to compare the results with other studies. One way around this issue is to show numerical values in the figures. Some studies included an LCA analysis but only cited results from other LCA studies rather than actually performing the LCA within their studies (e.g., [20]). In these cases it should be clearly stated in the methodology of the papers.

In terms of the coverage of the entire life cycle of BIPV, most studies focused on the materials and manufacturing of the PV systems, some included transport. In general, studies tend to exclude or use very simplified assumptions for the end-of-life stage. Future LCA studies need to give more emphasis on the end-of-life stage, even if the uncertainties might be high or assumptions need to be made. BIPV systems can also influence building energy performance [21]. This needs to be taken into account in LCA.

As an emerging technology, BIPV suffer from barriers such as data availability and uncertainties induced by rapid technology change. Therefore, there is a need for more “Anticipatory”

LCA studies that incorporates technology forecasting, risk analysis and stakeholder engagement in order to synthesise the available social, environmental, and technical knowledge [22]. In addition, there appears to be no study comparing BIPV with standalone PV systems and other types of renewable energy systems. Therefore, more research needs to be directed towards this area in order to understand the advantages and disadvantages of BIPV in the context of sustainable energy development.

4. Conclusions

BIPV is an important new technology with potentially huge environmental benefits. This review of the existing literature on LCA of BIPV suggests that it is still premature to determine the comprehensive environmental performance in relation to other energy technologies. Differences in scope and methods of existing LCA studies make it difficult to compare different studies and draw useful synthesis. Further research should focus on developing clear and consistent terminology, using LCA approaches, collecting data on the effects of BIPV on building energy performance as well as comparisons with other energy technologies covering a wide range of environmental impact categories.

5. References

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