Solar Energy Materials & Solar Cells 156 (2016) 75–82

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Life cycle assessment of dynamic building integrated photovoltaics

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ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
28 March 2016
Accepted 10 April 2016
Available online 4 May 2016

Keywords:
Dynamic photovoltaics
Life cycle analysis
Multi functional envelope
BIPV
Adaptive shading

ABSTRACT

We assess the environmental impact of a dynamic, adaptive, building integrated photovoltaic (BIPV) systems. Such systems combine the benefits of adaptive shading with facade integrated solar tracking, thus reducing the building energy demand, and simultaneously generating electricity on-site. The inventory for the life cycle assessment (LCA) was acquired using production data, and Energy Plus simulations to calculate the building energy demand. The impact assessment was conducted according to ISO 14040 and ISO 14044 standards using the Eco-invent database and openLCA as an analysis tool. The embodied environmental impact of the dynamic BIPV solution is higher than a static alternative due to the added control system, electronics, actuators, and additional supporting structure, resulting in higher life cycle impacts. However when accounting for the systems multi-functionality aspect, i.e. savings through adaptive shading to the building's heating, cooling and lighting loads, the embodied environmental impact can be offset, making the ASF an interesting alternative for BIPV. We also conduct a sensitivity analysis to investigate modifications to the actuator type, control system, and location and find that none of the investigated parameters overturn the key findings. The analysis ultimately enables us to provide design recommendations for future dynamic BIPV installations.

1. Introduction

Buildings are at the heart of society and currently account for 32% of global final energy consumption and 19% of energy related greenhouse gas emissions [1]. Nevertheless the building sector has a 50–90% emission reduction potential using existing technologies, and widespread implementation could see energy use in buildings stabilise or even fall by 2050 [1]. Within this strategy, building integrated photovoltaics (BIPV) has the potential of providing a substantial segment of a building's energy needs [2]. Even the photovoltaic (PV) industry has identified BIPV as one of the four key factors for the future success of PV [3].

Recent developments regarding efficiency and costs of thin film BIPV technologies, in particular, CIGS, have brought new design possibilities [4–7]. Their lightweight nature and customisable shapes allow for easier and more aesthetically pleasing integration into the building envelope. In addition, less power is required to actuate them, thus facilitating the development of dynamic envelope elements due to their reduced weight [8].

Dynamic building envelopes have gained interest in recent years because they can save energy by controlling direct and indirect radiation into the building, while still responding to the desires of the user [9]. This mediation of solar insolation can offer a reduction in heating/cooling loads and an improvement of daylight distribution as seen in Fig. 1 [8]. Interestingly the structure and mechanics required for dynamic envelopes couples seamlessly with the structure and mechanics required for facade integrated PV solar tracking. The use of light weight PV as an adaptive envelope material enables it to also benefit from on-site energy production. Furthermore, it provides a new way of aesthetically integrating PV panels onto buildings. The balance of electricity production and adaptive shading can in some cases offset the entire energy demand of an office space behind the envelope [10]. We have proposed one possible combination of these technologies as an Adaptive Solar Facade (ASF) [11]. An example of an ASF can be seen in Fig. 2.

The design of an ASF comes at an added cost. The additional electronics, actuators, and supporting structure adds further embodied CO_2 to the product. It is therefore important to conduct a life cycle impact assessment (LCA) to analyse whether the life cycle environmental impacts are favourable, compared to a more classic system. It is also important to see how variations in design can alter the green house gas (GHG) reduction potential of the technology. Aspects such as the chosen actuator, control system,

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http://dx.doi.org/10.1016/j.solmat.2016.04.017
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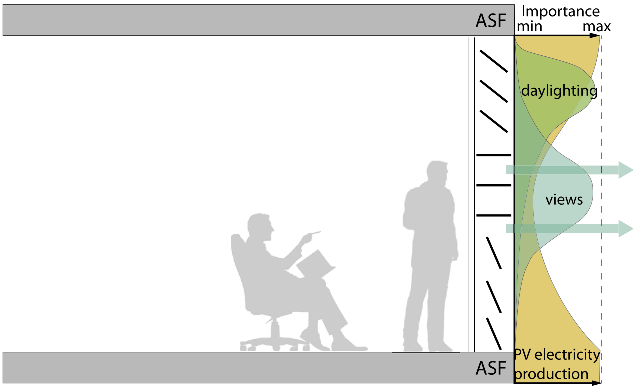

Fig. 1. The facade acting as a mediator between the interior and exterior environment, while fulfilling various functions [11].

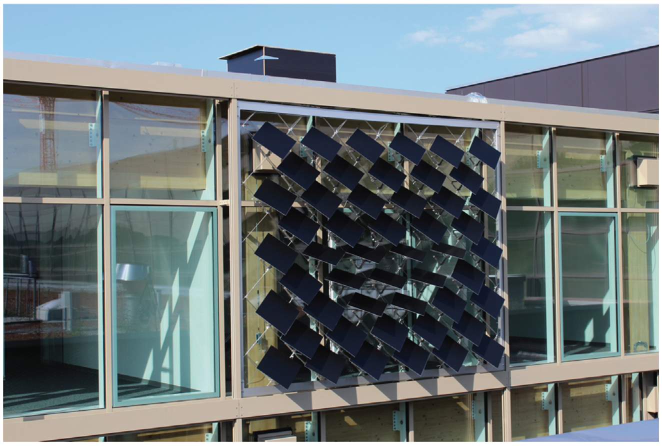

Fig. 2. An example of an ASF constructed at the House of Natural Resources [11].

and location of operation can have an impact on environmental performance.

The state of the art literature assesses existing photovoltaic technologies [12–14], and the balance of systems (BOS) which includes all other components of a photovoltaic system [15]. This has not, however, been expanded to dynamic BIPV systems, and in particular, systems that combine the benefits of adaptive shading and electricity production.

In this paper, we investigate the environmental performance of an ASF and compare it to existing static photovoltaic systems. We also investigate (1) a system expansion including the heating ventilation and air conditioning (HVAC) savings through adaptive shading, (2) design variations of the ASF, (3) the operational emissions of a building, with and without an ASF, and (4) the sensitivity of the LCA to its location and design.

The remainder of the paper is organised as follows. The following section introduces the ASF and the used LCA methodology. In Section 3, we present the results of the LCA analysis. Section 4 discusses the results and provides design guidelines. Section 5 concludes the paper.

2. Methodology

In this section, we detail the inventory, Energy Plus simulation methodology, important assumptions, and the LCA evaluation method. The assessment considers the environmental impacts of the production, operation, and disposal of an ASF. We assume a lifetime of 20 years based on the product warranty of the PV panels. The impact assessment is performed according to the ISO 14040 and ISO 14044, and is performed in four stages: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation [16].

1. *Goal and scope definition*: This paper primarily assesses carbon emission reductions therefore the global warming potential (GWP) impact category is primarily assessed. The assessment also looks at six other major ReCiPe midpoint indicators: terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), human toxicity potential (HTP), metal depletion potential (MDP), and photochemical oxidant formation potential (POFP). These categories are most relevant to the technology and most widely used in existing literature [17]. The functional unit is the electrical power production of the system in kWh.
   The scope of the assessment, respectively the system boundary, is summarised in Fig. 4. We analyse the manufacture, dynamic actuation, maintenance, and disposal of the solar facade. The scope comprises of a cradle-to-grave approach, where transport to and from site is taken into account. In order to account for the multi-functionality aspect of the ASF (i.e. electricity production and shading benefit), we carry out a sensitivity analysis and expand the system boundary including operational energy savings through adaptive shading. As the life cycle inventory (LCI) background database we use Ecoinvent v3.1 [18] with the cut-off system model.[2] That means impacts are allocated to the primary use of the product and it receives no credit for the provision of recycled material. Once a product is disposed or recycled, it leaves the system boundary and the recycled product comes burden-free.
2. *Inventory analysis*: The Ecoinvent v3.1 database is used as the main LCA database [18]. A detailed description of the inventory is found in Sections 2.1 and 2.2.
3. *Impact assessment*: The assessment is based on the IPCC 2007 methodology [19]. The GWP assessment is performed using the OpenLCA assessment tool [20]. In the assessment, we also compare the emission factor (EF) of an ASF with other PV systems. The emission factor is expressed as

$$EF = \frac{GWP}{G} \qquad \left[\frac{\mathrm{kgCO_2} - eq}{\mathrm{kWh}}\right] \qquad (1)$$

   where (G) is the electricity production in (kWh).
4. *Interpretation*: The results of the LCA analysis (not including shading effects) are compared with other facade integrated PV technologies. We then perform a system expansion to also include the effects of adaptive shading to the system. Finally a sensitivity analysis is conducted which is further described in Section 2.3.

2.1. Embodied life cycle inventory

The mechanical components of an ASF can be broken into four parts: a PV panel, actuator, cantilever, and a cable net supporting structure. The PV panel, actuator and cantilever combine to form a dynamic PV module, which is then mounted on a cable net supporting structure. An exploded view of these components can be seen in Fig. 3. There are also additional electronics which exists off

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[2] http://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html – *Accessed*: 8.2.2016.