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Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies

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ABSTRACT

Here, we review 33 life cycle assessment (LCA) studies of thin-film photovoltaic (PV) technologies that have had a holistic coverage in their assessments and/or have included ecodesign aspects. Only five of them were found to have a comprehensive life cycle and impact coverage, and their analyses highlighted the importance of (i) including the entire life cycle of the PV system, in particular the often-omitted disposal stage, and (ii) assessing all relevant impact categories and not just climate change or energy requirements to minimise the risk of burden-shifting. Out of the 28 studies embracing ecodesign considerations in parts of the PV life cycle, the analysis of the eleven of them addressing primary energy demand during module production suggests that electricity consumption during the metal deposition processes is a top contributor and should be prioritised by PV technology developers. A similar analysis of the ten studies having included the balance of system components (BOS) in the assessments showed that these contribute significantly to most environmental impact categories. Beyond recommending that stakeholders in the PV field rely on LCA to support decision-making and to guide scientific research and technological development, we strongly advocate LCA practitioners to include the entire PV system, including the BOS, to identify ecodesign opportunities without risking potential burden-shifting across the different parts of the system and across impact categories.

1. Introduction

Low-carbon energy technologies are essential to support climate change mitigation strategies and address rapid growth of global electricity demand. According to the International Energy Agency's (IEA) BLUE Map scenario, wide-scale deployment of low-carbon technologies is needed in order to meet electricity demands in 2050 while cutting greenhouse gas (GHG) emissions from power generation by 76% compared to 2007 [1]. Renewable energy sources are expected to contribute significantly to this effort with the BLUE Map scenario suggesting an increase in the combined share of solar, wind and hydropower from 16.5% of total electricity generation in 2010 to 39% in 2050. With respect to photovoltaics (PV), the global installed capacity of 135 GW in 2013 is envisioned to rise to 1721 GW by 2030 and 4674 GW by 2050 according to the High Renewables scenario planned by the IEA in its 2014 technology roadmap for solar photovoltaic energy [2]. These projected PV installed capacities could profitably be integrated into building structures, where they could form mini-grids and sustain self-production and self-consumption. In particular, a deployment in urban areas not only onto residential buildings but also onto other types of buildings, e.g. offices or supermarkets, could bring a good match between the demand and the daytime supply of electricity [3].

In Europe, which has pioneered the deployment of photovoltaics, PV technologies are expected to contribute to the European Union's (EU) energy efficiency targets by improving the energy performance of the building sector (Directive 2012/27/EU). There is a growing consensus that building-integrated photovoltaic (BIPV) systems will play a major role for achieving EU's target for nearly zero-energy buildings (NZEB) [4]. In addition to generating electricity, BIPV systems perform building envelope functions by replacing building elements, e.g. windows, tiles, shingles and blinds. It is therefore important to account fully for these multi-functionalities when estimating financial and environmental costs and benefits. In this regard, a distinction between wafer-based and thin-film PV technologies is necessary as the latter presents significant advantages over the former in BIPV applications, such as lower weight and lower installation costs as well as improved flexibility and optical semi-transparency [5,6].

In that context, it is important to ensure that such development and deployment of the PV technologies be made with as low

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environmental impacts as possible [7,8]. A number of studies have thus warned against risks posed by the global deployment of PV systems at the terawatt scale of installed capacity, e.g. the pressure on critical materials like rare earth metals from different solar cell technologies [6,9–11]. To address these environmental problems in a holistic manner, life cycle assessment (LCA) can be used. LCA is a decision-support tool that enables the quantification of all relevant environmental impacts throughout a system's life cycle from raw materials extraction through manufacturing and use/operation of the system up to its end-of-life, according to ISO 14040/14044:2006 standards [12,13]. It is conducted iteratively through four phases: goal and scope definition; life cycle inventory (LCI) analysis; life cycle impact assessment (LCIA); and, interpretation [13]. LCA has been widely used for investigating the environmental impact of PV technologies, and LCA practitioners were recently provided with methodological guidance issued by the IEA [14]. Until now, LCA applications to PV technologies have mainly had two purposes: (i) to document environmental performances of specific technologies and compare them to other renewable and non-renewable energy systems; and (ii) to identify environmental hotspots and guide scientific research and technological development.

The ecodesign of energy-related products is a crucial factor in the EU strategy on Integrated Product Policy (Directive 2009/125/EC). It is seen as an effective tool to improve energy efficiency as well as support industrial competitiveness and innovation by promoting the better environmental performance of products throughout the Internal Market. According to the Directive, ecodesign of energy-related products such as PV modules is defined as the 'integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle'. The current work relates to the latter purpose of utilising LCA as a tool for ecodesign, with a focus on BIPV applications and thus thin-film PV systems.

Until now, most review papers of LCA studies covering thin-film PV technologies have limited their focus to collecting results on GHG emissions and energy-related indicators such as cumulative energy demand (CED) and energy payback-time (EPBT), and comparing performances among different PV and renewable technologies [15–23]. Table S.1 illustrates those limitations, also in relation to the technological scope and thin-film PV coverage. Only a few review papers go beyond this scope, and consider other environmental impact categories (LCA term for classes representing environmental issues of concern e.g. climate change, land use, resource depletion) [24–27] or examine contributions of specific system components to the total environmental burden [28,29].

Overall, existing review papers lack a systematic consideration of all possible environmental issues (beyond climate change), and an explicit description of which processes or parts of the PV life cycle were considered by the LCA studies under review. These considerations are critical within the LCA methodological framework. Only by considering all environmental impact categories and the entire PV life cycle, including the often-omitted disposal stage, the shifting of a potential environmental burden from one life cycle stage to another or from one environmental problem to another can be identified and possibly avoided [12]. Otherwise, potential trade-offs might be missed, and environmental burden-shifting might take place, e.g. focusing on reducing GHG emissions while inadvertently increasing other nonetheless relevant impacts [30]. Examples of such relevant impacts include damages to ecosystems and human health caused by emissions of toxic substances or metal depletion, e.g. rare earth metals [31–33]. Finally, most review papers in the scientific literature lack an ecodesign perspective, where the identification of the so-called environmental hotspots, i.e. life cycle stages, system components or processes where the largest impacts stem from, are rarely associated with ecodesign recommendations relevant to PV technology developers.

The purpose of this study is therefore to address these gaps. Taking all studies addressing relevant impact categories throughout the entire life cycle of the PV systems, including the often-omitted disposal stage, we aim to investigate how results of past LCA studies of thin-film PVs can be used to identify bottlenecks and opportunities for technological improvement and mitigation of environmental impacts. Also, by identifying and critically reviewing ecodesign aspects of LCA studies across thin-film technologies, we aim to highlight the value of using LCA as a strategic decision-support tool to guide scientific research and technological development [31], and not just document the environmental performance of the system under study. The intended audience of our work includes both thin-film PV technology developers and LCA experts. We believe that effective ecodesign of thin-film PV requires a collaborative effort and expertise in both fields, according to international standards of environmentally conscious design for electrical and electronic products that stipulate that "environmentally conscious design requires collaboration and contributions of all stakeholders along the supply chain" [34].

2. Methods

2.1. Technological scope

The review scope includes LCA studies of thin-film photovoltaic technologies suitable for building integration, and excludes concentrated PV systems and product-integrated PVs. Studies that examined multifunctional systems with combined results such as green roofs, solar houses, and water desalination systems were deemed outside the scope of this study and were thus disregarded. Thin-film photovoltaic technologies include commercial technologies, cadmium telluride (CdTe), copper indium gallium diselenide (Cu(In, Ga) Se_2 or CIGS), as well as amorphous and nanocrystalline silicon (a-Si and nc-Si); and, emerging technologies, copper zinc tin sulphide (Cu_2ZnSnS_4 or CZTS), zinc phosphide (Zn_3P_2), perovskite solar cells (PSC), organic photovoltaics (OPV), dye-sensitized solar cells (DSSC), quantum dot photovoltaics (QDPV), and gallium arsenide (GaAs) were included as thin-film despite requirement for wafers as templates for crystal growth [6].

2.2. Collection of studies

Only scientific journal papers written in English and published from 2000 and onwards were considered in the review. A screening step using the Scopus database (http://www.scopus.com/) was used and complemented by a check for citing and cited papers of all relevant papers with case studies and reviews of LCA applied to thin-film PV (see also Table S.1). An additional screening step was made using Google Scholar (https://scholar.google.com/) to identify more recent literature published until mid-2015.

2.3. Analysis and classification of studies

The collected studies were evaluated with respect to the extent of their coverage of the PV life cycle, the range of the included environmental impact categories, and the inclusion of ecodesign recommendations. The studies were grouped in two sets described below.

Set 1 comprises LCA studies that cover the entire PV life cycle, and include more than one impact category. Fig. 1 illustrates the system boundaries of the entire PV life cycle (cradle to grave) used as reference in the review. It encompasses the production stage with all upstream processes, including the resource extractions;