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Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies

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ABSTRACT

Recent developments in organic photovoltaic technology demonstrate the possibility of easily printable, light, thin, and flexible solar panels with fast manufacturing times. Prior life-cycle assessment studies show potential for organic photovoltaics to lower the environmental footprint and shorten the energy and carbon payback times compared to conventional silicon during the production of a solar cell on a watt-for-watt basis. This study extends such analyses beyond the manufacturing stage and evaluates the prospective cradle-to-grave life-cycle impacts of organic photovoltaics compared with conventional ones. Two systems (solar rooftop array and portable solar charger) were chosen to illustrate how different product integrations, duration of use and disposal routes influence potential environmental benefits of organic photovoltaics while informing researchers on the prospects for continued development and scaling-up this technology. The results of the life-cycle assessment showed that environmental benefits for organic photovoltaics extend beyond the manufacture of the photovoltaic panels, with baseline cradle-to-grave impacts for both long-term uses (rooftop arrays) and short-term uses (portable chargers) on average 55% and 70% lower than silicon devices, respectively. These results demonstrate that further reductions can be leveraged by integrating organic photovoltaics into simpler devices that take advantage of their flexibility and ability to be used in applications that are less constrained by conventional technology. For example, organic photovoltaic charging units showed life-cycle impacts more than 39–89% lower than silicon along with energy and carbon payback times as short as 220 and 118 days, respectively.

1. Introduction

The last 4 decades of solar photovoltaic (PV) development has seen a range of proposed and viable technologies, spanning from conventional single-crystal (s-Si) and multicrystalline silicon (m-Si) to second generation panels such as amorphous silicon (a-Si), cadmium telluride (CdTe) and cadmium indium gallium selenium (CIGS) [1]. More recently, much research and development has gone into the so-called *third generation* (3rd-gen) PV technologies including dye-sensitized (DSC), perovskite, quantum dot (QD) and organic (OPV) cells, for instance [1]. As recently as 2014, the PV market was dominated by conventional silicon technology (e.g. m-Si), capturing over 90% of the world's annual PV production [2]. Silicon PVs are approaching price parity with energy sources such as coal [3], and since 2008 there has been a steady drop in market prices of silicon [4]. Although this trend may stabilize and even reverse in the near-term [5], it has reduced the incentive to invest in and develop 3rd-gen PV technologies that are not yet as cost competitive [6].

On the other hand, 3rd-gen PVs such as OPVs have other compelling characteristics including being extremely thin, flexible, requiring small amounts of active material and solution-based roll-to-roll (R2R) processing [7]. These characteristics make the ease of production, installation and use of OPVs particularly attractive, while potentially reducing the environmental impacts of OPVs compared with conventional silicon technology. Life-cycle assessment (LCA) is an environmental management tool that can be used to calculate the environmental and human health impacts of products, including PV-devices [8]. LCA has been used to show that on a watt-for-watt comparison of solar panel manufacturing, OPVs have the potential to reduce carbon emissions and energy consumption by over an order of magnitude compared to silicon [9,10]. Similar reductions of 1–2 orders of magnitude have been

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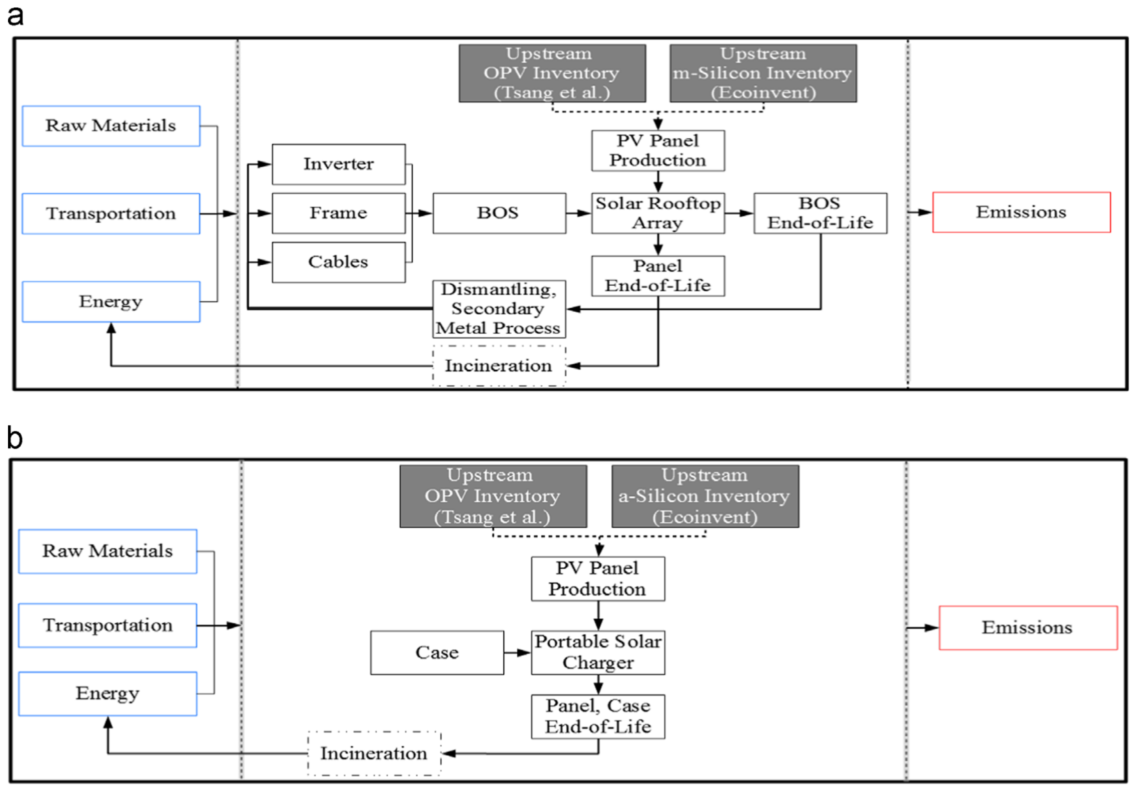

Fig. 1. System boundaries for (a) S1 (rooftop array) and (b) S2 (portable charter). Incineration is just one of the end-of-life scenarios modeled in the LCA and is shown for clarification of how the energy recovery is considered in the life-cycle inventory. Further description of the upstream system boundaries for the organic photovoltaic and silicon panels are given in Tsang et al. [12].

seen across a wider range of LCA impacts such as photochemical oxidant formation, water depletion and human health and eco-toxicity, for example [11,12].

OPVs are known to be less efficient [1,10,13,14] and have shorter lifetimes [15] compared to conventional silicon PVs. Consequently, environmental benefits seen during OPV manufacturing might be offset by the cumulative use and replacement of exhausted OPV panels over an entire lifetime of its service [16]. In addition, important questions remain regarding how PV panels can and will be disposed of at their end-of-life [17]. This infrastructure is lacking for conventional PVs [18], with landfilling being a default solution. It is similarly uncertain how OPV panels might be disposed of since they are not yet used commercially, thus it is important to anticipate the influence disposal routes will have on the life-cycle impacts of these technologies.

Given these considerations, the objective of this paper is to evaluate the potential cradle-to-grave life-cycle impacts of OPVs and conventional silicon technologies. The nature of this paper examines both forward-thinking design aspects of the OPV geometry (e.g. all-polymer active layers), different types of uses that OPVs can serve and currently feasible end-of-life options for two contrasting long-term versus short-term systems: a solar rooftop array (25-years) and a portable solar charger (5-years).

2. Methods

2.1. Goal and scope

The LCA was conducted according to International Organization for Standardization (ISO) 14040:2006 [19] and 14044:2006 [20] guidelines and the International Energy Agency's (IEA) recommendations for implementing LCAs for PV technology [8]. A cradle-to-grave assessment was completed, comparing the life-cycle impacts for polymer-based OPV technologies with conventional silicon technology.

All life-cycle stages and impacts from raw materials extraction, materials processing, product manufacturing, use, end-of-life considerations were included. Two systems were considered in order to better inform the potential role OPVs could play in the energy procurement and consumer product sectors. System (S1) was defined by a functional unit of an average kWh of electricity generation over 25 years using a solar rooftop array (Fig. 1), while System 2 (S2) was defined by a functional unit of an average 10 Wh of electricity generation over 5 years via a portable charging-device Fig. 1.

All foreground inventory data are explained in detail in the following sections, while relevant background data was taken from the attributional Ecoinvent v2.2 (The Ecoinvent Association, Zurich) [21] life-cycle inventory. An attributional inventory was chosen in order to determine baseline life-cycle impacts of OPVs, as opposed to assessing the consequential life-cycle impacts that arise from changes in the photovoltaic market and energy market due to OPV production and use, which are currently unknown. All transportation requirements for incoming foreground chemicals and materials were taken into account using 100 km truck and 600 km rail transport, while outbound waste materials were estimated using 10 km truck transport [21]. Capital equipment (e.g. buildings for solar panel production) was excluded from the OPV inventory as such environmental burdens are often negligible when considering the entire life-cycle and life-time of a product [22]. Where applicable, co-products resulting from the end-of-life treatment option of the solar panels (e.g. electricity from incineration) were handled as avoided products using system expansion. Energy production from incineration was assumed to replace an average European medium-voltage electricity production mix (RER) defined by Ecoinvent v2.2. Only electrical energy, as opposed to thermal energy was