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Comparison of life cycle environmental impacts of different perovskite solar cell systems

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ABSTRACT

Perovskite solar cells have attracted enormous attention due to their low cost and high power conversion efficiency. However, the use of toxic metals such as lead in the perovskite dye and the disposal methods of perovskite solar cells cause grave concerns about their environmental impacts. Inorganic and lead-free perovskite solar cells have been developed to overcome the disadvantages of lead-based organic perovskite solar cells, a development that involves different materials and manufacturing processes to fabricate different perovskite solar cells. In order to understand and develop an environmentally friendly perovskite solar cell technology, comprehensive environmental impact assessments have been conducted in this study on five typical perovskite solar cells, using an attributional life cycle assessment (LCA) approach. The results indicate that $MAPbI_3$ and $FAPbI_3$ perovskite solar cells have relatively larger environmental impacts than $MASnI_{3-x}Br_x$, $CsPbBr_3$, and $MAPbI_2Cl$ perovskite solar cells based on a 1 cm^2 active area solar cell system, and this result can be explained by the different amounts of organic solvents used in the device fabrication. In addition, gold production makes the largest environmental impact contribution to perovskite solar cell systems, and the substitution of silver or aluminum for gold can significantly reduce the total environmental impact scores. For disposal methods, incineration with energy recovery is found better than landfill.

1. Introduction

Much attention has been drawn to clean energy due to the depletion of fossil fuels and increase of energy demand. Abundant solar energy is one of the promising clean energy resources that have been continuously studied in recent years [1]. In the past two decades, the scientists have dedicated their efforts to improving the performance of solar cell devices, especially third-generation solar cells. Third-generation solar cells aim to reduce costs by largely increasing power conversion efficiencies, but maintaining the economic and environmental cost advantages of thin-film deposition technologies [2–4]. In this context, dye-sensitized solar cells (DSSCs) have been proved to be one of the most valuable third-generation solar cells. However, the presence of organic solvents in DSSCs has always been seen as a problem due to their flammable and leaking characteristics [5]. To solve this problem, one group of scientists has attempted to replace the liquid organic electrolyte with polymeric materials, while another scientific group has paid their attention on finding more promising dye materials. In 2011, perovskite was first reported as an alternative promising material to replace the conventional organic dye in DSSCs [6], which attracted increasing attentions in the following years.

Perovskite dye shows remarkable optical absorptions over a broad range, a capacity that enables efficient light harvesting in very thin films [7]. Moreover, it exhibits long charge-carrier diffusion lengths relative to the absorption depth of incident light [8–10], which means that almost all photo-excited species in perovskite are able to reach the charge collection electrodes and can result in superior photovoltaic performance. The perovskite solar cells also display low non-radiative carrier recombination rates, which can increase the open-circuit voltage and give rise to a substantial efficiency advantage [11]. The diverse perovskite dye materials and fabrication methods, which involve lead-free perovskite dye and low temperature fabrication, have also been developed in recent years to further enhance the perovskite solar cell as a renewable energy source. In current research, the conversional efficiency has exceeded 20% [11,12], and the maximum theoretical value of perovskite solar cells can be greater than 30% [13].

The perovskite compounds have the ABX_3 structure, where the A and B are two cations of different sizes, and X is a halogen ion. Typically, the metal cation B is Pb^{2+} or Sn^{2+}, and the halogen ion can be F^-, Cl^-. Br^-, or I^-. The A cation is selected to balance the total charge,

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and it can be organic or inorganic. Since the cation must fit into the rigid and relatively small cuboctahedral hole formed by the 12 nearest neighbor halogen atoms, the cation A is expected to be limited [14]. Currently, two organic cations and one inorganic cation are appropriate choices for the perovskite structure, and they are methylammonium, formamidinium, and cesium [9,15,16]. Among all the perovskite solar cells, the most commonly studied is the methylammonium lead iodide ($CH_3NH_3PbI_3$) perovskite solar cell, but concerns have been raised about its relatively high toxicity potential, expensive counter electrode, and short life span [17,18].

To overcome these problems, different types of perovskite solar cells have been developed in recent years [19–21]. In order to answer the question whether the perovskite solar cell is environmentally sustainable [22,23], lead-free perovskite solar cells, such as methylammonium tin triiodide ($CH_3NH_3SnI_3$), have been developed in recent years. To lower the cost of precious metals used in counter electrode, different types of carbon-based counter electrodes have been developed [24]. However, there are still some problems with regard to the carbon counter electrode due to its inherent fragility and poor scratch resistance [25]. Low-cost, non-precious transition metals, such as Cu, Ni, W and Mo, were investigated to reduce the fabrication cost [26]. The instability of the methylammonium lead iodide perovskite solar cell is caused by a combination of such external factors as moisture, oxygen, temperature, UV light, and such internal factors as ion migration, electro-migration and interfacial reaction [13]. Several strategies have been proposed, such as device encapsulation, protection of the organic compounds with metal oxides, addition of interfacial modifier cesium bromide, coatings with multifunctional fluorinated photopolymer [27], and change of perovskite materials. In recent years, formamidinium lead iodide ($CH(NH_2)_2PbI_3$) and methylammonium lead iodide chloride ($CH_3NH_3PbI_2Cl$) have been designed to obtain a longer life span [7,28]. Formamidinium lead iodide shows surprisingly enhanced carrier transport properties, compared with methylammonium lead iodide [29], while methylammonium lead iodide chloride displays a strong increase in the overall charge diffusion length with the presence of a chloride source [30]. Moreover, inorganic cesium lead iodide ($CsPbBr_3$) perovskite solar cells have been developed to increase the availability of potential perovskite materials [16]. In addition to overcoming the disadvantages of perovskite solar cells, an increasing attention has been concentrated on large-scale fabrication. Thanks to their high conversion efficiencies and simple manufacturing procedures, there is a promising potential for the solid-state perovskite solar cells to be commercialized in the following years [11]. Multiple attempts have shown that scale-up of the perovskite solar cell module can be realized with increased stability [31–33].

With multiple perovskite solar cells being developed for industrial commercialization in the near future, the environmental impacts of these technologies have raised concerns, but these impacts have not been compared systematically. On the one hand, researchers used different assumptions when analyzing the environmental impacts of perovskite solar cells, and these differences resulted in varying perspectives on the environmental impacts. For example, Gong et al. compared the life cycle environmental impacts of TiO_2- and ZnO-based solid-state perovskite solar cells, and they claimed that 82.5 and 60.1 g CO_2 eq. could be released into the environment to generate 1 kWh of electricity, with 7.78 kWh of manufacturing energy needed to fabricate 1 m^2 perovskite solar cells [34]. Espinosa et al. examined the toxicity of solid-state perovskite solar cells, and found that about 5.48 and 5.24 kg CO_2 eq. were produced to generate 1 kWh of electricity, with 0.146 and 0.108 kWh of process energy to produce 1 m^2 solar cells [19]. Serrano-Lujan et al. compared the life cycle assessments of tin-based perovskite solar cells with those of lead-based solar cells studied in earlier research, and found that 10.6 kg CO_2 eq. was generated in the process of producing tin-based perovskite solar cell [22]. Celik et al. investigated the environmental impacts of two low-cost manufacturing methods of solid-state perovskite solar cells, and found that 120–180 g CO_2 eq. was produced from low-cost perovskite solar cells, with 140–228 kWh of manufacturing energy to fabricate 1 m^2 solar cells [35]. Most of these studies start with divergent assumptions regarding manufacturing energy and solvent usage, and these assumptions make comparison of the studies difficult. On the other hand, none of these articles includes a range of typical perovskite solar cells. In this paper, the cradle-to-grave environmental impacts of five types of perovskite solar cells, including methylammonium tin triiodide ($MASnI_{3-x}Br_x$), methylammonium lead iodide, formamidinium lead iodide, cesium lead iodide, and methylammonium lead iodide chloride, have been systematically investigated through a comprehensive life cycle assessment approach. The methods and results presented in this study can be used to support sustainable development and deployment of the perovskite solar cell technologies in the near future [36].

2. Methodology

2.1. Goal and scope definition

The goal of this study is to assess and compare the life cycle environmental impacts of available perovskite solar cell technologies, and to identify and understand the potential routes for sustainable development of perovskite solar cell technology. In this study, a hybrid Life Cycle Assessment (LCA) model has been used to assess the environmental impacts of five representative perovskite solar cells with different power conversion efficiencies (PCEs). These five perovskite solar cells represent five different types: one inorganic cell and four organic-inorganic hybrid cells, one of which is lead-free and three of which are lead-based but differ in cations and halogen ion. The architectures of these five perovskite solar cells are the same, consisting of a fluorine tin doped oxide (FTO) layer, a compact layer, a mesoporous layer, a perovskite layer, a hole transport material (HTM) layer, and a gold layer; the difference is primarily in the perovskite layer. In order to facilitate the comparison of the five different perovskite solar cells, two boundaries are set in this study: one is from raw material extraction to end-of-life (cradle-to-grave); the other one is from raw material extraction to system assembly (cradle-to-gate), which serves to validate the results using our previous study [37]. The system boundary from cradle to grave is shown in Fig. 1 with a solid line; the system boundary from cradle to gate is shown in Fig. 1 with a dashed line. The functional unit in this study is defined as 1 cm^2 active area for solar cell generation, and it is interchangeable with 1 kWh under specific solar insolation, performance ratio, lifetime, conversion efficiency, and active area ratio. Technically, the active area ratio can be calculated by dividing the area of the perovskite layer by the area of the FTO glass. In this study, the active area ratio is chosen to be 60% [38]; the solar insolation, at 1700 kWh/m^2/y; the performance ratio, at 0.75; and lifetime, at 1 y (where y is the abbreviation of year).

From Fig. 1, system manufacturing consists of raw material extraction, component manufacturing, disposal of wastes from component manufacturing, and solar cell assembly. Raw material extraction involves all the processes used to acquire raw materials and to transform them into useful materials, such as FTO glass and the titanium paste that is a major component in the mesoporous layer. The data concerning component manufacturing is derived from the experiments conducted in our lab to fabricate the solar cell components and also from various literature. Wastes from component manufacturing involve all the waste solvents generated from the fabrication process spin-coating. According to the literature, about 90% of the material used in spin-coating is wasted [19,34] and for the purpose of this study, the waste solvents are assumed to be sent to a wastewater treatment plant. A solar cell is assembled after the fabrication of each component has been completed. For comparative analysis with other perovskite solar cell systems, the impact of transportation is omitted by this LCA study, which assumes that perovskite solar cells have similar impacts from transportation as other solar cell technologies.