Energy 145 (2018) 700–709

Contents lists available at ScienceDirect

Energy

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

A comparative life cycle assessment of chalcogenide/Si tandem solar modules

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ARTICLE INFO

Article history:
Received 6 November 2017
Received in revised form
4 December 2017
Accepted 24 December 2017
Available online 4 January 2018

Keywords:
LCA
Life cycle assessment
Tandem solar cells
Environmental impacts

ABSTRACT

Tandem technologies offer potential price reductions and higher efficiencies of PV modules. The high band gap nature of chalcogenides like CIGS, CZTS and AZTS makes them excellent materials for use on top of a Si base tandem cells. Nevertheless, along with the search for new technologies, there is also the concern about the environmental impact that its lifetime can cause. A comprehensive life cycle assessment for CIGS/Si, CZTS/Si and AZTS/Si tandem solar modules was not reported to date. This work compares the environmental impacts of Si and chalcogenide/Si tandem solar modules, assessing global warming potential, human toxicity potential (cancer and non-cancer effects), freshwater eutrophication potential, freshwater ecotoxicity potential, abiotic depletion potential and the energy payback time of these technologies. The results of this study show that compared with Si, CIGS/Si presents worse environmental impacts for most of the categories but, on the other hand, CZTS/Si and AZTS/Si present better outcomes for most of the impacts categories. We can also say that higher efficiency of these tandem technologies could potentially reverse that result. This LCA provides design advice for the R&D community, showing which structure has the best environmental outcomes and which processes should be optimized to achieve better results.

1. Introduction

Silicon (Si) based solar cells have been developed worldwide and their efficiency has continually increased. However, single-bandgap cells have a limited performance because of the incomplete utilization of photon energy. Multi-junction cells can capture the photon energy more efficiently because of the difference between the band-gaps of the bottom and top cells [1,2].

Based on the Shockley-Queisser (S-Q) detailed-balance model, the photovoltaic (PV) single-junction solar cell limiting energy conversion efficiency is 30%, for a band gap of 1.1 eV and considering an AM1.5 solar spectrum [3]. Moreover, thin-film materials have been developed, providing potentially low cost, flexible geometries and using relatively small material quantities. Thin-film technologies have led mainly to three options for PV modules that are amorphous and microcrystalline Si films ("micromorph cells") and chalcogenide compounds such as CdTe or CIS (copper indium diselenide or disulphide) [4]. Other chalcogenide examples are copper indium gallium diselenide (CIGS) and copper zinc tin sulfide (CZTS) technologies which have a confirmed terrestrial cell efficiencies (measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C) of 21.0 ± 0.6% and 10.0 ± 0.2%, respectively [5].

CIGS is a semiconductor with very high optical absorption coefficient because it is a direct band gap material. It has a chalcopyrite crystal structure and its band gap can be tuned between 1.0 and 2.4 eV by varying the In/Ga and Se/S ratios [6] and efficiency of approximately 15.7 ± 0.5% for high bandgap [5]. The possibility of a high band gap makes CIGS an attractive material in tandem solar cells for using it on top of a Si base cell [6].

CZTS (kesterite) is very similar to CIGS in optoelectronic and crystallographic properties, as well as in methods of fabrication. However, CZTS has lower efficiency when compared with CIGS solar cells [5]. Another problem with CIGS is relative scarcity of indium in Earth's crust is [7]. Nevertheless, researchers are showing

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https://doi.org/10.1016/j.energy.2017.12.130
0360-5442/

that CZTS is the most promising alternative to CIGS [8] and CZTS/Si tandem cells are expected to be of increasing interest. The first step was to demonstrate CZTS epitaxy on Si, which was already confirmed [9–11].

Recently, alternatives to CZTS have been proposed where either Zn or Cu is replaced by other elements in order to generate higher band gaps [12]. One example is Ag_2ZnSnS_4 (AZTS), wherein Ag replaces Cu [13]. The possibility of high bandgaps, where AZTS can achieve a direct band gap of 2.0 eV [14], makes AZTS/Si tandem solar cells an interesting possibility.

Along with these developments, there is also a concern with the environmental impacts that the production process, use phase and end-of-life may cause. Life Cycle Assessment (LCA) is a methodology used to analyse any product or process from an environmental perspective [15]. The initial step of an LCA is defining the goal and scope of the study. The next phase is to produce an inventory, followed by the impact assessment, where the inventory data is translated into environmental impacts. Finally and based on the results, recommendations are made in order to have lower environmental impacts [16].

To date, a comprehensive LCA on CIGS/Si, CZTS/Si and AZTS/Si tandem solar modules has not been reported to the best of author's knowledge. This work compares the environmental impacts of chalcogenide/Si tandem solar modules, with the aid of GaBi LCA software [17] to assess different environmental impacts of these technologies.

2. Methods

LCA is a methodology used to structure and qualify material and energy flows and the associated environmental impacts produced by products and services during their life cycle. This method has four main steps: goal and scope definition, life-cycle inventory, impact analysis and interpretation of the results [18].

2.1. Goal and scope

The goal of this LCA is to assess six different impact categories: Global warming (GWP), human toxicity potential - cancer effects (HTP-CE), human toxicity potential – non-cancer effects (HTP-nCE), freshwater eutrophication (FEuP), freshwater ecotoxicity (FEcP) and abiotic depletion potential (ADP) of chalcogenide/Si (CIGS/Si, CZTS/Si and AZTS/Si) tandem solar modules compared to Si p-n junction (p/n) and heterojunction with intrinsic inverted layer (HIT) solar modules. It is also part of the goal of this LCA to calculate the energy payback time (EPBT) of these solar modules.

The functional unit to be used in this analysis is defined as 1 kWh of generated electrical energy and the system boundaries of this LCA are shown in Fig. 1. The system inputs and outputs depend on the goal and scope, as well as the assumptions made. This LCA is for cradle-to-grave, which means that the analysis initiates with the raw materials necessary for the cells' production and finishes at the modules' end of life.

In this study we are assuming a life time of 20 years for all modules and that all the modules produced go to the landfill after the end-of-life, since recycling processes are not mature and are outside the scope of this specific study. However, the impacts of disposal may be shown to be significant and some studies have already shown that recycling can improve the environmental impacts of PV cells [19–21]. Because of that, LCA for recycling needs to be developed for future work. The module materials we are considering are ethyl vinyl acetate (EVA) encapsulant, aluminium frame, polymer back-sheet, cover glass, tabbing and lead-containing solder, as are commonly used in Si PV modules. As a simplifying assumption, we are considering that all cell and module production is in China, although it is well known that it actually occurs in many other countries too [22]. We are using GaBi software [17] to calculate the impacts described above. GaBi models every element of a product or system and calculates the environmental impacts from all stages of the life cycle of any product. It also provides an easily accessible and constantly refreshed databases, including its own internal database and Ecoinvent [23], that details the energy and environmental impacts of raw materials and processed components [17].

The EPBT (calculated by Equations [1] and [2]) is the relation between the energy input during the PV module life cycle (including manufacturing, installation, operation, and end of life) and the annual energy electricity generated by the module [24]. In other words, it represents how long a PV system needs to operate to recover the energy that went into making, operating and disposing system [25].

$$\mathrm{EPBT} = \frac{\mathrm{E_{INP}}}{\mathrm{E_{PV,annual}}} \times \eta_{\mathrm{grid}} \tag{1}$$

$$\mathrm{E_{PV,annual}} = \mathrm{G \cdot A \cdot \eta \cdot PR} \tag{2}$$

where E_{INP} is the energy input, $E_{PV,annual}$ is the annual energy output, η_{grid} is the grid conversion efficiency (0.315 [23]), G is the annual insolation (1700 kWh/m^2/year [26]), A is the area, η is the module efficiency and PR is the performance ratio (0.75) [26].

The three chalcogenide/Si tandem solar technologies chosen to be analyzed are CIGS/Si, CZTS/Si and AZTS/Si, whose structures are shown schematically in Fig. 2a,b, and c respectively.

In this LCA we are assuming that chalcogenide/Si tandem solar cells have an ideal tunnel junction and neither electrical resistance nor optical loss at the interface between the top and bottom cells. We also assume an adjustment of the thickness of the top cells to match the currents generated in each sub-cell of a tandem structure. For high bandgap CIGS we are assuming 1 μm, which is thinner than the normal absorber layer (i.e. 2 μm) [27]. For CZTS the first experiments are focusing on demonstration of CZTS epitaxy on Si [9–11]. Based on these experiments we are considering in this analysis a thickness of 0.5 μm, which is approximately half of the normal absorber layer (i.e. 1 μm) for CZTS.

A thickness of 0.5 μm is also assumed for AZTS for an appropriate comparison in relation to environmental impacts. Besides that, for this technology it is shown that the use of a CdS buffer layer leads to device efficiencies less than 0.5%. This is why we are assuming that an alternative stack with a FTO and MoO_3 buffer layers, which can deliver a higher efficiency for this cell is implemented [13]. We are assuming the HIT silicon as the bottom cell in this case, because the AZTS is a n-type cell [28].

2.2. Life-cycle inventory

The life cycle inventory (LCI) data for the Si (p-n and HIT), CIGS/Si, CZTS/Si and AZTS/Si tandem solar cells and modules are shown

Fig. 1. System boundaries.