Solar Energy 137 (2016) 317–327

Contents lists available at ScienceDirect

Solar Energy

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

Life Cycle Assessment and eco-efficiency of prospective, flexible, tandem organic photovoltaic module

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 16 August 2016
Accepted 18 August 2016

Keywords:
Organic photovoltaic (OPV)
Tandem cell
Life Cycle Assessment (LCA)
Global warming potential (GWP)
Energy payback time (EPBT)
Levelized costs of electricity (LCOE)

ABSTRACT

Organic photovoltaic technology has reached a sufficient maturity to enable commercially viable products for integration into buildings with power conversion efficiencies up to about 5%, for example, using a roll-to-roll (R2R) processing of single bulk heterojunction devices technology. This paper reports on a Life Cycle Assessment (LCA) and eco-efficiency analysis of prospective tandem organic photovoltaic (OPV) modules which have been manufactured to the most part in pilot environments. To realistically model the LCA and eco-efficiency a power conversion efficiency of both 10% and a more modest 8% were used with lifespan scenarios of 15 and 20 years. The tandem OPV modules modelled in this study have: a cell stack consisting of new advanced materials such as nano-sized zinc oxide, nano-sized silver, and semiconductor polymers; a light management structure; and new flexible PET based encapsulation with organic and inorganic barriers. This tandem technology was modelled assuming an industrialized production based on real and estimated resource consumption and pollution data from an existing roll-to-roll pilot OPV plant and from material suppliers together with projected costs. Established multi-silicon (multi-Si) and cadmium-telluride (CdTe) photovoltaics were taken to benchmark the environmental impacts in production and the expected levelized costs of electricity. The results of the modelling show that the production of 1 m^2 tandem OPV module represents only approximately 3–10% of the impacts of 1 m^2 of the benchmark multi-Si or CdTe modules when the global warming potential (GWP), cumulative energy demand (CED), eco-toxicity, and metal depletion environmental impacts are considered. The results also show the energy payback time of a tandem OPV at facade is only 18–55% of that of the benchmarks, and the GWP is just 12–60% of that of the benchmarks. An eco-efficiency comparison indicates that, for applications where photovoltaic modules cannot be optimally oriented towards the sun, a flexible tandem OPV might be a superior alternative to multi-Si and CdTe modules.

1. Introduction

United Nations ranks two Sustainable Development Goals (SDGs) as the most important for the transformational challenge in developed countries: to take urgent action to combat climate change and its impacts and to ensure access to affordable, reliable, sustainable, and modern energy for all (United Nations, 2015). The emerging organic photovoltaics (OPV) belong to the latest generation of technologies in solar power generation, which offers the benefits of flexibility, design freedom for integration in a variety of applications, low weight and alternative production methods requiring relatively low initial capital investments (International Energy Agency, 2014). This technology could contribute to a double-decoupling of the economic growth from resource consumption and environmental burdens while providing an economic and socially sound alternative of power supply. OPV technology reached sufficient maturity to realize commercial products produced with halogen free and nano-sized advanced material for solution based roll-to-roll (R2R) processes. Single bulk heterojunction devices with power conversion efficiencies (PCEs) of 3–5% (Nisato, 2015) are commercial available representatives of this technology progress.

Research and development (R&D) of OPVs is ongoing, including high-performing materials, tandem stack architectures and light management structures suitable to achieve higher PCE in OPV modules. The European SUNFLOWER project aimed at developing tandem, solution-processed OPV, which can be industrialized. This work reports on the assessment of the life cycle environmental impacts and eco-efficiency of an industrialized production with advanced materials and a prospective tandem OPV module.

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http://dx.doi.org/10.1016/j.solener.2016.08.025
0038-092X/

Even if the development of tandem OPV needs further R&D before commercialization, it is important to establish a framework that allows estimations for the expected environmental impacts and the foreseen eco-efficiency of such modules. This is relevant on one hand for positioning the technology in the market and to provide input for further technological development on the other. The developed framework can easily be re-scaled on module level in case of research-related optimization of the PCE and lifetimes.

Energy payback time (EBPT), the global warming potential (GWP) and the eco-efficiency of electricity generation for a facade application are discussed. Multi-silicon (multi-Si) and cadmium-telluride (CdTe) are used as benchmarks to show benefits and weaknesses of the prospective tandem OPV compared to photovoltaic (PV) technologies with a high market penetration (International Energy Agency, 2014).

As the LCA for the production is based on the functional surface of OPV (*e.g.* 1 m^2) results for EBPT, GWP and eco-efficiency can be simply adjusted for future higher power generation yields of tandem applications.

Based on results from ongoing research and development work we assume a realistic PCE target of 8% on module level with two operational lifespan scenarios of 15 and 20 years to cover the expected lifespan range The feasibility of roll-to-roll printing of tandem OPV modules with inks based on water or non-halogenated solvents was demonstrated, though still with limited power conversion efficiencies (Andersen et al., 2014). However PCEs higher than 10% have been reported from You et al. (2013), Li and Brabec (2015) and Bin Mohd Yusoff et al. (2015) fabricated under research conditions. Therefore a PCE of 8% for a prospective tandem OPV seems realistic for commercialized products. Nevertheless an optimistic PCE of 10% also was considered for the eco-efficiency analysis. R&D work of SUNFLOWER was focused to provide advanced materials and processes suitable for such an industrial production of OPV.

The presented framework will help to further assess the technology and to foster improvements *e.g.* minimizing the dependency on scarce, expensive and environmentally challenging materials such as indium tin oxide (ITO) for electrodes by substitution with organic compounds and nano-sized silver.

2. Methodology

The established methodologies of Life Cycle Assessment (LCA) and eco-efficiency analysis were applied. A LCA is standardized in ISO 14040:2006 (ISO, 2006). The Life Cycle Inventory (LCI) is based on data provided from SUNFLOWER project partners, from literature, own calculations and from LCA database ecoinvent 2.2 (Ecoinvent Centre, 2010). Sources are shown in Table 1 and the data model is presented in Section 4.2.1. Data for PV benchmark technologies are taken from ecoinvent 2.2 and de Wild-Scholten (2013). The LCA was elaborated with EMIS v5.7© software (Carbotech, 2012).

In an eco-efficiency analysis an economic factor is taken into consideration in addition to the environmental impacts, i.e. the levelized costs to produce the energy unit 1 kW h, and presented against the impact indicators in x-y graphs to derive efficiency frontiers for generation technologies.

3. Description and expected industrialization and application of the flexible tandem OPV prototype

3.1. Structure, functions and production

The OPV module presented in this work is flexible, opaque, and is solution-processed produced by R2R manufacturing except for the deposition of the inorganic barriers of the encapsulation and the index material of the light management. It comprises a light management, the tandem cell stack and encapsulation layers as shown (Fig. 1) and described in the subsections below.

It includes newly developed substances such as quinoxaline, thiophene-rich high-band gap semiconducting polymers, buffer inks based on nano-sized zinc oxide getters based on nano-sized zeolites as adhesive additive, organic barrier lacquer, nano-sized silver particle paste for electrodes and water based conductive poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) inks.

3.1.1. Function and production of the light management

With light management the PCE can be improved approximately by 10% relative to the original structures (Mayer et al., 2016). The principle is based on guiding the light via micro- and nanostructures to maximize its absorption in the active photo-absorbing layers of the OPV tandem stack. Light management structures can be optimized for different OPV stacks or conditions of application. The technologies considered for production are compatible with large-scale manufacturing and include hot-embossing of polymer foils, sol-gel coating and structuring by UV curing; performance can be further improved in some cases by adding higher refraction index materials such as zinc sulfide (vacuum- or solution-processed).

3.1.2. Function and production of the tandem cell stack

The OPV cell stack consists of a front cell with a high-band gap (HBG) semiconducting polymer, a recombination layer, and a rear

Table 1
Overview of the input materials for the production of one square meter (1 m^2) flexible tandem OPV and their environmental impact represented with the CED, GWP, metal depletion and ecotoxicity indicator. The amounts of the input materials include the solvents in the inks and 1–2% production losses of the R2R production of the tandem stack and lamination with the encapsulation. A detailed list of the input materials is presented in the LCI in the supporting material.

Input materials/layers	Amount per m^2	Unit	CED [MJ-eq/m^2]	GWP [g CO_2-eq/m^2]	Metal depletion [$/$m^2$]	Ecotoxicity [CTU/m^2]	Sources
Encapsulation	1.01	m^2	21.7–22.4	1001–1042	3.00E−03 to 3.67E−03	3.45E−01 to 3.81E−01	This work
PEDOT:PSS ink (1.3 wt%)	127.9	g	19.9–23.0	1220–1408	3.51E−03 to 4.27E−03	1.21 to 2.06	This work, García-Valverde et al., 2010
Light management	1.01	m^2	13.8–15.0	819–891	6.71E−03 to 9.61E−03	8.18E−01 to 1.17	This work
Nano-silver ink (64 wt%)	4.0	g	11.9–12.6	777–835	2.38E−02 to 2.99E−02	1.03–1.17	This work
Nano zinc oxide ink (1 wt%)	28.0	g	10.5–11.2	541–599	2.05E−03 to 2.72E−03	1.77E−01 to 2.05E−01	This work
PCBM in solution (3% wt)	4.048	g	8.0–8.4	318–337	3.50E−04 to 4.26E−04	5.18E−01 to 9.32E−01	This work, Anctil, 2011
PET substrate	1.01	m^2	6.4–6.6	237–249	9.79E−04 to 1.22E−03	1.07E−01 to 1.17E−01	Ecoinvent 2.2
Semiconducting polymers in solution	2.691	g	5.3–5.8	359–406	6.93E−04 to 8.25E−04	4.54E−01 to 4.85E−01	This work
Epoxy adhesive	18.0	g	1.2–1.3	59–61	4.42E−06 to 6.26E−06	2.15E−02 to 2.50E−02	Ecoinvent 2.2
Coating and other processes	1.25	kW h	6.5–7.3	180–196	1.85E−03 to 2.23E−03	2.06E−01 to 2.54E−01	This work, Schilinsky, 2014