Solar Energy Materials & Solar Cells 120 (2014) 692–700

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Life cycle analysis of organic tandem solar cells: When are they warranted?

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ARTICLE INFO

Available online 23 October 2013

Keywords:
Organic photovoltaics
Tandem solar cells
Multi-junction solar cells
Roll-to-roll
Life-cycle assessment
Energy payback time

ABSTRACT

One approach to use solar radiation more effectively in solar cells is to stack, in series, multiple photoactive layers with complementary absorption spectra. Such devices are often termed tandem or multi-junction solar cells. The larger number of different materials and processing steps involved in their making when compared with the single junction solar cell has to be justified and compensated by a higher efficiency. A central question to ask is how much energy you need to invest in a system in order for it to produce energy and return the investment at least once and preferably a number of times. As an initial investigation into the potential viability of the tandem or multi-junction approach we have engaged in a detailed analysis based on the manufacturing energy for each step within the tandem module supply chain for full ambient processing of thin flexible polymer tandem solar cells prepared entirely by roll processing methods. We present a comprehensive overview of relevant research results on how the energy consumption affects the energy balance when using single and multi-junction solar cells. Based on the above question we calculate the minimum efficiency that the tandem or multi-junction should present to determine the minimum energy payback time; that is whether (or when) the increase in materials use and complexity of the tandem architecture is compensated by better performance. After analysing the performance and the consideration of a series of technical improvement opportunities, we project that the tandem solar cell has to be ~20% higher performing than the corresponding single junction solar cell to be warranted. We also highlight that there is a range in the reciprocal EBPT–efficiency relationship where the tandem solar cell is an advantage. Specific to polymer and organic solar cells are however that they embody very little energy and this implies that the single junction may be an advantage, especially in cases where land mass is not critical.

1. Introduction

There is an increased focus on environmentally benign manufacture of energy technologies and special focus is devoted to technologies with a low degree of cumulative energy demand (CED) as this is a prerequisite for sustained growth and survival in the future. The objective of covering a large part of the energy demand with low carbon emissive energies is ambitious in some countries. As an example, Denmark has adopted the target of having 100% of renewable energy by 2050, which means that a lot of effort and funding must be put into the development of these currently non-existing alternative energies. In addition the cost must be low since it is expected that the turnaround due to a relatively shorter operational service life will cause an increase in the costs of electricity. In spite of the fact that these new technologies, such as wind and solar energy, require a high degree of initial investment, when they start operating and competing on the market, they have the particular advantage that their marginal costs are zero [1]. The Danish energy strategy is aligned with the forecasted decrease for photovoltaic electricity costs, with the levelized cost of electricity (LCOE) from PV estimated to be 15 €ct/kWh by 2050 [2].

From the range of PV technologies, so far, only silicon (Si) based PV technologies would be applicable on a large scale. Thin-film PV technologies such as CIGS- or CdTe-based solar cells are not an option since there is not even a fraction of the needed indium or tellurium available in the earth crust to fully cover the future energy demand [3]. However, the energy demand for producing Si based solar cells is on the order of several thousand MJ per square metre [4,5]. In the other extreme the organic photovoltaic (OPV) family presents the lowest energy embedded and as a technology it is potentially cheaper globally for the reasons that an energy producing unit can be manufactured in a much shorter timespan

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http://dx.doi.org/10.1016/j.solmat.2013.09.013

than any other energy technology by use of high-throughput roll-to-roll methods [6]. In addition there is no requirement for production in a fixed location due to the requirement for only a very low capital invest in equipment or by modification of existing equipment (typically printing and web conversion machinery). Despite having low power conversion efficiency (PCE) and short lifetimes, OPV can thus excel due to its low capital expenditure for large-scale manufacture [7–10]. Recent cost and life-cycle analysis studies suggest that organic solar cells can be competitive with other PV technologies if modules with 7% PCE and 5 years lifetime can be produced, which would represent a cost of 0.19 €/kWh [11].

Nevertheless, the competitiveness of OPV can only be achieved if design is applied to the choice of materials and processing in order to have sustainable products and OPV will be meaningful in the very large-scale approximation. Traditional laboratory OPV has employed indium in the transparent indium–tin-oxide (ITO) electrode and it is clear that in the very large-scale approximation this is not viable as shown in several studies that in addition to the indium scarcity also found limitations in the large energy requirements [12] and also the high monetary cost of ITO sputtering deposition [11]. Efficient alternatives to ITO have however been developed [13] and the era of OPV has already begun; it has been heralded as the PV technology with the most steadfast decrease in energy payback time (EPBT): The time needed to recover the energy that has to be employed during its manufacture. This period for OPV is ranging from 2.02 to 0.20 years. ITO-based solar cells are in the upper end of this range [12] and the ITO-free devices are in the lower end of the range [14]. More recently, when polymer solar cells were integrated in a device such a laser pointer, with carbon-based electrodes, it was found that they could payback the energy in less than 4 months [15]. Known technology improvement opportunities could be utilised for further reductions in manufacturing energy costs. Developments in low temperature processing, larger substrate width, larger geometric fill factor, have been proven to promote reductions in EPBT down to just several days [14]. Furthermore, OPV has among all PV technologies one of the largest energy return factors, i.e. in their entire lifetime the energy required for their manufacturing can potentially be paid back a large number of times in a short time: 5–10 times during 1–2 years of lifetime respectively.

One approach to more efficiently use solar radiation in solar cells that has been proposed [16] is to stack, in series, multiple photoactive layers with complementary absorption spectra, which ultimately raise the power conversion efficiency (PCE). This next generation of organic photovoltaic solar cells is known as tandem solar cells, which combine high performance, stability and low cost—only if they are produced by roll-to-roll procedures. Multi-junction OPV structures have been the subject of life-cycle assessments recently [17], and it has been found that they embed energies of around 10 MJ/W_p. The devices in that specific case comprised small molecules and were based on small scale laboratory devices with successive evaporation of the layers. This naturally leads to some inaccuracy in data when using it for scaling and furthermore the evaporation processes will incur at least 10 times higher embodied energy than for printed/coated devices. The restriction in those devices is not only the high cumulative energy demand, but also the impossibility of being produced in large-scale, at least until higher efficiencies do balance the required investment in energy.

This research paper brings together expertise from chemistry and technology and through life-cycle assessment we seek to analyse the real manufacture of tandem polymer solar modules in a large-scale, by considering their whole life cycle and we forecast what levels should be reached in order to have competitive solar cells. Our aim within this work is to design low-carbon footprint OPV type to ultimately reduce the barriers to entry in the markets, extending the ability to produce them if possible in all regions of the world.

1.1. The tandem solar cells

Having two or more solar cells stacked one after another, the tandem solar cell device concept, enables maximisation of the photon absorption and thus an increase in light energy harvesting. In the traditional tandem cell each junction is based on a different absorber material. The efficiency is thus increased by the spatial separation of the separate absorption of high-energy photons and low energy photons. In a typical double-junction cell the architecture comprises a front cell with a high-bandgap material, interconnecting layers (ICLs), and a rear cell consisting of a low-bandgap material. The number of layers usually exceeds 10; since there are more materials involved as compared to single junction devices, the question is what can be gained from additional junctions? In principle the open circuit voltage and high external quantum efficiency (EQE) can be higher at long wavelengths: $V_{oc}=E_g-0.6$ V, FF=65% and EQE=65%.

The first organic tandem solar cells with small-evaporated molecules were reported as early as 1990. It took more than 10 years before research on organic tandem solar cells became more commonplace [18]. From the first published polymer tandem solar cells with 0.57% efficiency, in 2006 [19], until the record for tandem cells is currently held by You et al. with a PCE of 10.6% [20], many strategies have been employed in polymer tandem cells ranging from new interconnecting layers yielding a PCE of 6.5% PCE through current matching [21], adding more junctions such as the triple junctions explored by Li et al. [22] with a reported PCE of 9.6%. The area that currently develops most rapidly is the materials synthesis of new low band gap materials [21,23,24]. The tandem solar cells procedure we have based the study-published in this issue [16]-makes use of the same active layer polymers, since they provide compatibility with roll-to-roll processing.

1.2. Description of the layers and their processing

Single junction OPV modules have been produced and have been available in large quantity for more than 6 years in our complete coating stations specially designed for medium scale serial production of solar cells by roll-to-roll methods. The various layers are typically printed and coated by using flexography, slot die and rotary screen methods, and the processing conditions have been detailed in Table 1. In the single junction case different silver grid–PEDOT:PSS composite electrodes are used in the front and the back electrode. The front electrode comprises a water-based silver ink with 60% silver content (PFI 722 from PChem) and the PEDOT:PSS is an aqueous dispersion (PH1000 from Heraeus). Then the electron transport layer is coated, which is a nanoparticle ZnO dispersion (prepared in acetone), and the active layer, typically using P3HT:PCBM, are both slot die coated. In the tandem solar cell case [16] there are two more PEDOT:PSS layers, F010 that belongs to the front cell and then AL-P 4083 that can be seen as belonging to in the back cell. Both are water-based dispersions from Heraeus. Another ZnO and active layer are coated as well symmetrically under the same conditions; but in the back cell the active layer is thinner. To complete the tandem cell the back electrode is deposited; again silver and PEDOT:PSS, but now PV410 from DuPont and F010 from Clevios, respectively. Finally, solar cells are encapsulated in line by using a UV curable adhesive from Delo (Katiobond LP655), and 62 μm barrier material with UV protection from Amcor.

2. Methodology

A life-cycle assessment is a powerful tool for directing efforts towards low carbon energy technologies, since it targets research