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A projection of commercial-scale organic photovoltaic module costs

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ABSTRACT

Organic photovoltaics (OPVs) are a recent technology that has gained much attention as a potential low cost power source. Despite this promise, there is a lack of published studies that address the likely cost of commercial-scale OPV modules. In this work, an engineering study estimate has been performed to determine the projected cost of mass-manufactured OPV modules. The materials, production capital and operating costs have been calculated and sensitivity analyses performed to determine the parameters of greatest economic influence. Significantly, the model includes a calculation of the costs required to establish bulk manufacturing of the current high cost speciality materials components, encompassing synthesis and associated chemical plant design. The economic modelling reveals that the calculated mass-manufactured OPV module costs are considerably lower than current literature estimates, with OPV modules costed at $7.85 per square metre with an uncertainty of ± 30%. Total module cost was found to be most sensitive to the plastic substrate prices, while the production rate did not have a significant impact on module cost for rates above ~ 50 m^2/min. The results highlight the future cost potential of OPV technology and can be used to assist with scale-up planning.

1. Introduction

Emerging solar energy technologies such as solar thermal [1], thin-film silicon cells [2], dye-sensitised cells [3] and OPVs [4] have become increasingly well-established as potential low cost power sources. OPVs made from conducting polymers and plastic are particularly attractive as they can use abundantly available raw materials and offer the prospect of highly scaleable manufacturing techniques [5,6].

While still in the early stages of development compared to conventional photovoltaics, OPVs have been improving rapidly largely due to recent research efforts. The highest efficiency laboratory scale devices so far have been independently certified at 10.0% conversion of sunlight to power [7], and concurrently much work has been focussed on using printing and coating techniques to cheaply mass manufacture OPV devices [8,9]. In light of this, OPVs are best described as a promising technology on the verge of commercialisation.

Knowledge of the economics of large-scale production is a factor critical to the successful scale-up and commercially viable mass manufacture of OPV. However, very limited work has been conducted in this respect, with only a few authors considering the cost of producing OPV modules. The cost targets required for viable OPV implementation were determined in an early study by Dennler and Brabec, with their opinion that these cost targets would be easily achievable in the future [10,11]. Later work by Kalowekamo and Baker predicted a cost for large-scale OPV based on data for dye sensitised cells and conventional silicon cells, and made the assumption that OPV would follow a similar cost pathway to scale-up [12]. Another study by Roes et al. did not present a cost per square metre, instead making an estimate of the cost per Watt-peak (W_p) of OPV on glass, with an assumed efficiency of 5% and lifetime the same as for conventional silicon cells [13]. In an alternative approach, the costs of a pilot scale OPV manufacturing process were calculated by Krebs et al. and, although this treatment does not consider the cost of full-scale production, it provides a useful insight into where the main costs are currently situated [14]. Subsequently, a revised estimate of module costs based on the same pilot process has been published, which includes a full breakdown of materials, capital and operating costs [15]. Since then Powell et al. examined the viability of OPV under different electricity price and weather scenarios, calculating a break-even target in the vicinity of $45/$m^2$, depending on location [16]. The OPV module costs and/or targets described in these studies are summarised in Table 1.

Although commercial viability will additionally depend on the OPV efficiency and lifetime, calculating the module production cost is the first step towards determining the potential of OPV as a feasible energy source. However, to date, previous published work has been based on the cost of small-scale chemical manufacturing

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Table 1
Review of recent estimates/targets for the cost of OPV modules.

Authors	System assumptions	Module cost/target	Reference
Dennler and Brabec (2008) and Dennler et al. (2009)	No system costed, presented cost targets necessary for viable large-scale production	Target of €25–110/m^2 (Converts to $\$36\text{–}159/m^2$)	[10,11]
Kalowekamo and Baker (2009)	Used data from DSC, conventional silicon and thin-film production. Organic solar cell was based on C_{60}, CuPc and SnPc with 1 μm layer thickness, ITO electrode, 4-tertiary butylphenol layer.	$\$49\text{–}139/m^2$	[12]
Roes et al. (2009)	Assumed cell efficiency of 5%, lifetime equal to crystalline silicon cells, glass substrate.	€2.80/W_p (Converts to $\$180/m^2$)	[13]
Krebs et al. (2010)	Reel-to-reel pilot plant using slot die coating and screen printing. Cell structure was ITO, ZnO, P3HT:PCBM, PEDOT:PSS, Ag ink.	$\$130\text{–}900/m^2$ (best guess $\$220/m^2$)	[14]
Nielsen et al. (2010)	Reviewed costs, markets and intellectual property of small-scale OPV production and compared to other solar energy technologies.	Target of $<\$0.70/W_p$	[17]
Azzopardi et al. (2011)	Reel-to-reel pilot plant using slot die coating and screen printing. Cell structure was ITO, ZnO, P3HT:PCBM, PEDOT:PSS, Ag ink.	€63.16–191.89/m^2 (Converts to $\$87\text{–}264/m^2$)	[15]
Powell et al. (2012)	Presented break-even targets, module costs used in the calculations were obtained from Kalowekamo and Baker [12]	$\$45/m^2$	[16]

and pilot-scale module production processes. Consequently, there is an urgent need for a full cost estimation of OPV modules fabricated on plastic substrates and produced by a large-scale manufacturing process. This paper provides the first cost estimation specifically for commercial-scale plastic OPV production by conducting an engineering planning and feasibility study estimate. The study is based on current OPV architectures and fabrication processes and models the effect of material production scale-up with associated sensitivity analysis. The results highlight the future cost potential of the technology and provide a basis for scale-up planning and energy cost calculations.

2. Methods

2.1. Basis of OPV cost calculations

Projections of future OPV module costs have been made by considering the design and costing of a large-scale OPV production plant, and accounting for the effect of production scale-up and increased demand for OPV technology on the price of materials. Standard engineering cost estimate methodology has been followed, as outlined by Peters et al. [18] and Sinnott et al. [19] amongst other authors. A planning/feasibility study estimate method (sometimes referred to as a Level 2 estimate [18]) was undertaken since it is the most appropriate method given the amount of information available at this stage. A specific device architecture (Fig. 3) has been chosen as a case study for this costing method. In addition, a full life cycle analysis is beyond the scope of this work and considerations such as energy payback period are not addressed.

Fig. 1 shows the stages in the OPV production process based on generally accepted OPV fabrication methodology [20].

The material cost calculations were then based upon the following assumptions:

(1) The OPV fabrication process involves solution preparation, gravure printing of anode and active layers, physical vapour deposition of cathode, and encapsulation.
(2) The materials used were poly(3-hexylthiophene) (P3HT) and phenyl-C61-butyric acid methyl ester (PCBM) in a 1:1 ratio in chloroform, with an aluminium cathode, poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) and silver grid anode, and polyethylene terephthalate (PET) substrate and encapsulation.
(3) Current bulk commodities prices were used and were not considered likely to change significantly in the near future.
(4) A production rate of 60 m^2/min was assumed (corresponding to a 1 m web width moving at 1 m/s). This is well within the quoted capabilities of film metallisers [21] and printing/coating processes [8,22].

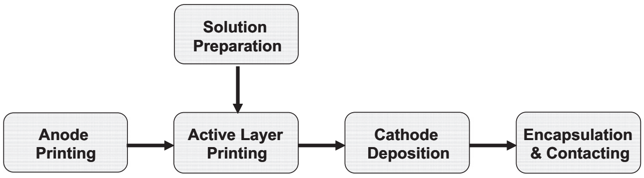

Fig. 1. Stages in the production process.

(5) The plant lifetime is 20 years.
(6) The plant operation was defined as 8 h per day, 5 days per week, 44 weeks per year (to allow for a standard 8 weeks maintenance per year).
(7) The labour and production costs were based on manufacture in a developed country (such as Australia or USA).
(8) Units of money are USD.

In addition, the sensitivity of the module cost to the key assumptions has been examined and is discussed in the results.

2.2. OPV module cost

The cost components of OPV module fabrication can be broken down into the categories shown in Fig. 2. The three major components of OPV production are: (a) the materials required to construct the module, (b) the capital cost of building a production plant and (c) the ongoing costs to operate the plant.

2.2.1. Material costs

The model is based upon a P3HT:PCBM system with PEDOT:PSS and silver grid transparent anode and aluminium non-transparent cathode with PET substrate and encapsulation, and copper electrical contacts. Consistent with standard device architectures, the dry thickness of the active and cathode layers were defined as 100 nm while the PEDOT:PSS layer was also 100 nm. The specific architecture chosen (Fig. 3) is representative of the OPV structures that are fabricated by many groups. This cost projection does not advocate a particular architecture but rather presents a case study and thus is a starting point for calculation. An architecture without indium-tin-oxide (ITO) has been selected. Whilst an ITO anode is often used in current module architectures, it is considered prohibitive to the commercial viability of large-area OPV products due to the high cost of indium metal, and work has already been conducted on examining the viability of alternatives [23,24]. Therefore, this calculation assumes the replacement of ITO with