Solar Energy Materials & Solar Cells 120 (2014) 9–17

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

A projection of commercial-scale organic photovoltaic module costs

Cara J. Mulligan, Mitchell Wilson, Glenn Bryant, Ben Vaughan, Xiaojing Zhou, Warwick J. Belcher, Paul C. Dastoor *

Centre for Organic Electronics, University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 22 December 2012
Received in revised form
16 July 2013
Accepted 30 July 2013
Available online 26 September 2013

Keywords:
OPV
Module cost
Materials
Production
Economic model

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 $\pm$ 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

* Corresponding author. Tel.: +61 2 4921 5426; fax: +61 2 4921 6907.
E-mail address: paul.dastoor@newcastle.edu.au (P.C. Dastoor).

0927-0248/\$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2013.07.041

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 \$36–159/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.	\$49–139/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.	\$130–900/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 \$87–264/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].
(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.

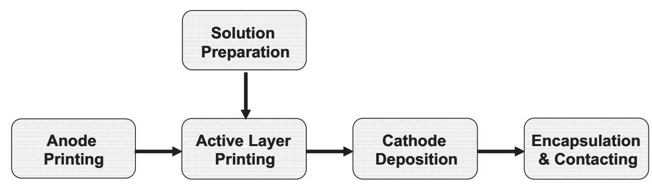

Fig. 1. Stages in the production process.

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

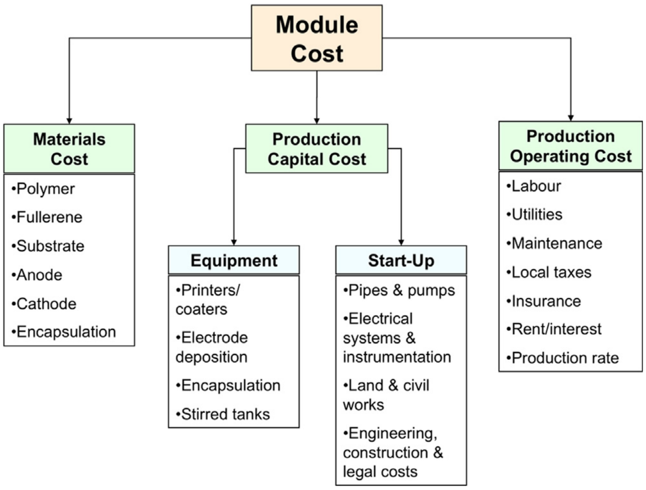

Fig. 2. Cost breakdown for the fabrication of OPV modules.

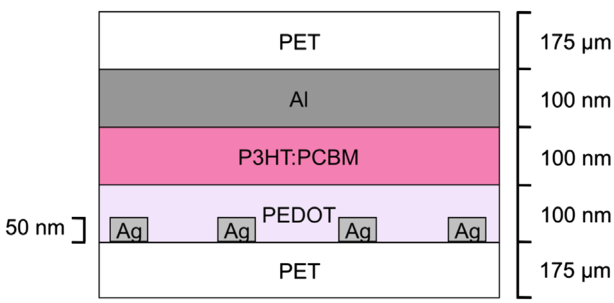

Fig. 3. Schematic of the architecture assumed for the modelled devices (not drawn to scale; the actual dimensions are indicated alongside the drawing).

another abundant or easily producible material such as PEDOT:PSS, which has been proven by several authors as an anode [25–34], with the highest device efficiencies of up to 4.2% [26]. For completeness a module cost sensitivity to ITO use has also been calculated using current ITO prices and is given in the results section. PET has been chosen as a substrate and encapsulating material as it is an example of a barrier film that is already well-established and mass-manufactured. Although more advanced barrier films are being developed and widely produced for this case study we used PET as a proxy for these materials. Similarly, an evaporated aluminium electrode has been chosen since it is a proven cathode material in OPV devices and metallised foils are already produced on a large-scale for use in industries such as the food industry. The research into new materials is ongoing and future OPV manufacturing plants may not necessarily use this exact structure, however it is provided simply as an example of a viable functional structure. A sensitivity analysis of materials costs has also been conducted.

2.2.1.1. Bulk materials costings. The material costs were divided into two groups. First, there are the materials for which bulk or commodity pricing is readily available. Consequently, aluminium, silver, copper, solvent and PET costs were based on the average 2011–2012 bulk commodity prices. Bulk materials prices were obtained from widely accessible online sources, for example the spot price of metals [35,36] and global trading/reporting websites [37,38]. Similarly, PEDOT:PSS is widely used as an antistatic agent and therefore the quantities required for large-scale production are already commercially available.

2.2.1.2. Speciality materials costings. P3HT and PCBM are both speciality chemicals made in small quantities so current prices do not reflect the commodity price of these materials in the case of large-scale production. Recent work by Osedach et al. examining the viability of polymers for OPV has shown that P3HT has the potential to be one of the least expensive polymers due to the relatively few steps required for synthesis [39]. They estimate P3HT costs of \$16.18/g when starting with 3-bromothiophene as the feedstock and using current materials and laboratory work-up costs. In order to determine accurate future pricing for P3HT and PCBM, analyses of the large-scale production processes of each of these materials was conducted to obtain figures for bulk costs. For each material the synthesis process was traced back to readily available raw chemicals and the plant equipment required for large-scale synthesis was modelled and costed. Plant operating costs for the materials synthesis facilities, including process heating needs, wages and overheads were determined using the methodology presented in the next section.

2.2.2. Fixed capital costs for production facilities

For both the speciality materials chemical synthesis plant and the OPV manufacturing facility, the fixed capital costs were broken down into: (1) equipment capital and (2) start-up costs and were calculated separately. The percentage of delivered equipment cost method [18] was used to calculate the fixed capital costs, giving an accuracy of $\pm$ 20–30%.

Equipment capital costs were calculated from current quoted equipment prices and scaled to the appropriate size using the widely accepted six-tenths factor rule [18]:

$$C_a = (C_b)X^{0.6} \tag{1}$$

where C_a is the cost of the equipment of the required scale, C_b is the known cost of similar equipment and X is the ratio of capacity of equipment a to b.

Start-up costs were estimated based on the percentage of the total equipment capital value as shown in Table 2 [18].

Total fixed capital costs were calculated by the following:

$$C_f = C_e + C_s + F_c(C_e + C_s) \tag{2}$$

where C_f is the total fixed capital cost (\$), C_e is the delivered equipment cost (\$), C_s is the start-up costs (\$) and F_c is the contingency factor, which is estimated at 8–10% for a solid/liquid handling process such as OPV production [18].

2.2.3. Operating costs for production facilities

The operating costs were calculated using the methods suggested by Peters et al. [18] and Sinnott et al. [19]. A production plant manufacturing 60 m^2/min of OPV modules was determined to have an operational labour requirement of 11 operators (two operators per unit operation plus one extra), 2 mechanical fitters and 2 electricians per shift, with a total of 5 shifts per week. Wages were costed at the current award rates in Australia [40]. Supervision and administration labour was calculated at 15% of operating labour [18].

Table 2
Start-up costs estimation.

Item	Equipment capital (%)
Bulk plant items (eg. pipes, pumps)	30
Instrumentation	25
Electrical systems	20
Installation	35
Site/civil works	40
Land	5
Contracting (engineering, construction and legal costs)	50

The required utilities for plant operation consist of electricity, water and waste disposal. Utilities costs were set at 10% of the final product cost [18].

Maintenance and replacement parts have been estimated to amount to 7% of the fixed capital investment amount annually, while operating supplies are estimated at 15% of operating labour [17]. Laboratory charges (for materials analysis and quality assurance testing) are expected to be 15% of the operating labour costs [17].

Local taxes will apply to the facility and these have been costed at 2% of the fixed capital cost, whilst insurance has been predicted to be 0.5% of the fixed capital cost [17]. As a conservative approach, the plants were assumed to be financed with a weighted average cost of capital of 15% per annum and payback period of 5 years. The weighted average cost of capital of 15% incorporates both a conservatively high interest rate and a minimum acceptable rate of return (MARR), based on other established renewable energy projects [41]. The sensitivity to the interest rate and payback period is presented with the results (Fig. 8 and 9). Other plant overheads were estimated at 60% of the total combined costs of operating labour, supervision and maintenance [18].

2.3. Expression for module cost

The module cost was calculated on a square metre basis, thus eliminating the need for assumptions of energy output and efficiency. The total module cost is the sum of the costs from the materials, capital costs and operating costs as outlined previously in Fig. 2. The mathematical expression for the module cost is:

$$\begin{aligned} \mathit{Module\ Cost}\ (\$/m^2) &= \mathit{Materials\ Cost}\ (\$/m^2) \\ &+ \frac{\mathit{Total\ Capital\ Cost}\ (\$)}{\mathit{Annual\ Production\ Rate}\ (\mathrm{m}^2/y) \times \mathit{Plant\ Lifetime}\ (\mathrm{y})} \\ &+ \frac{\mathit{Annual\ Operating\ Costs}\ (\$/y)}{\mathit{Annual\ Production\ Rate}\ (\mathrm{m}^2/y)} \end{aligned} \tag{3}$$

3. Results and discussion

On the basis of the module cost breakdown presented in Fig. 2, we have calculated the costs of the three major components of OPV production. The total module cost and cost breakdown were calculated as well as a sensitivity analysis of the cost dependence on materials and production rate.

3.1. Bulk materials costs

The bulk material costs used in the calculations are summarised in Table 3.

3.2. Speciality materials costs

As an illustrative example, the methodology used to determine the P3HT commodity pricing is summarised here, with a similar approach adopted for PCBM. The reaction scheme for the P3HT synthesis (Fig. S1 (Supplementary data)) was a combination of the syntheses outlined by Landman et al. [42], McCullough et al. [43] and Loewe et al. [44].

3.2.1. Basic plant design and equipment capital costs

A model chemical plant for the production of P3HT was designed and used in conjunction with the mass and energy balances to determine the type and scale of plant equipment required. Fig. S2 (Supplementary data) shows the schematic layout of the modelled chemical plant and the required equipment scale and costs are outlined in Tables S3 and S4 (Supplementary data) respectively. The plant costed has a production capacity of 55 kg/h of P3HT product. The capacity of the P3HT plant was based on a production rate of 100,000 kg per year (enough to supply 100 OPV manufacturing facilities each producing 1 m^2/s of product).

3.2.2. Plant start-up costs

The start-up costs for the modelled P3HT production plant were calculated using the data given in Table 2 and are presented in Table 4.

Table 3
Materials prices used in the calculations.

Material	Cost	Source
PEDOT:PSS (2 % solids)	$195 /kg	[37]
Silver Ink (70 % solids)	$2200 /kg	[37]
Aluminium	$2600 /t	[36]
PET	$1.40 /m^2	[37]
Solvent (chloroform)	$300 /t	[38]
Acrylic adhesive	$20 /kg	[37]
Copper contacts	$0.01 /piece	[37]

Table 4
Start-up costs for P3HT production chemical plant (rounded to nearest 1000).

Item	Cost ($)
Bulk plant items (eg. pipes, pumps)	666,000
Instrumentation	555,000
Electrical systems	444,000
Installation	777,000
Site/civil works	888,000
Land	111,000
Contracting (engineering, construction & legal costs)	1,110,000
Total with 10% contingency factor	5,006,000

Table 5
Annual operating costs for P3HT production chemical plant (rounded to nearest 1000).

Item	Cost ($/y)
Labour –plant operations	857,000
Labour –supervision & administration	129,000
Utilities (electricity, water, gas, waste disposal)	13,350,000
Maintenance and replacement parts	521,000
Operating supplies	78,000
Lab charges (quality control)	129,000
Local taxes	149,000
Insurance	37,000
Financing (average annual interest)	160,000
Plant overhead costs	904,000
Total	16,314,000

3.2.3. *Plant operating costs*

The operating costs for the modelled P3HT production plant were calculated using the methods outlined by Peters et al. [18], and are summarised in Table 5. The operating costs are quoted on an annual basis and the plant lifetime is assumed to be 20 years.

3.2.4. *Summary of speciality material costs*

By taking into account the calculations described in the preceding sections it is now possible to determine a commodity price for P3HT and, applying a similar methodology, PCBM. The relevant details for the synthetic processes are summarised in Table 6, together with the final commodity bulk pricing for each speciality material.

3.3. *Equipment capital costs for OPV production facilities*

Based upon the architecture for OPV design shown in Fig. 3, the equipment requirements of the OPV manufacturing facility were established and are listed in Table 7 together with their associated costs (based on list and quoted prices from leading manufacturers). Note that there are three separate printers in the production facility; one for silver grid printing, one for PEDOT:PSS printing and one for active layer printing.

3.4. *Start-up Costs for production facilities*

Table 8 outlines the start-up costs for the OPV production facility. Contracting professional personnel such as engineers, lawyers and construction managers represent the greatest start-up costs, while land costs are the least expensive item.

Table 6
Summary of figures used for calculation of materials costs for production of P3HT and PCBM.

	Feedstock chemicals	Price ($/kg)	Reagent stoichiometry	Other chemicals	Synthesis Ref.	Bulk Price ($/kg)
P3HT	Thiophene Bromine	0.05 1.41	5.9 17.7	Grignard reagents, Solvents	[42–44]	1180
PCBM	Fullerene Benzene Glutaric anhydride	10,000 1.05 3	3.3 6.7 6.7	*p*-tosylhydrazide, Solvents	[45]	13,700

Table 7
Estimated equipment costs for OPV module production facility.

Equipment capital item	Cost ($)
Reel to reel printer (including dryers & motors) x 3	8,554,000
Encapsulation and contacting unit	408,000
Electrode deposition/film metalliser	580,000
Enclosures for printer/coater	118,000
Mixer/sonicator	31,000
Solvent scrubber	7000
Delivery	970,000
Contingency factor (10%)	1,066,000
Total	11,735,000

Table 8
Start-up costs for module production facility (rounded to nearest 1000).

Start-up cost	Cost ($)
Bulk plant items (eg. pipes, pumps)	3,201,000
Instrumentation	2,667,000
Electrical systems	2,134,000
Installation	3,734,000
Site/civil works	4,267,000
Land	533,000
Contracting (engineering, construction & legal costs)	5,334,000
Contingency factor (10%)	2,187,000
Total	24,057,000

Table 9
Operating costs of an OPV production facility (rounded to nearest 1000).

Operating cost	Cost ($)
Labour – plant operations	705,000
Labour – supervision and administration	106,000
Utilities (electricity, water, gas, waste disposal)	4,950,000
Maintenance and replacement parts	2,506,000
Operating supplies	376,000
Lab charges (quality control)	106,000
Local taxes	716,000
Insurance	179,000
Financing (average annual interest)	770,000
Plant overhead costs	1,990,000
Total	12,404,000

3.5. *Operating costs for production facilities*

The operating costs for the OPV production facility are outlined in Table 9. The largest operating cost component is maintenance, followed by plant overhead costs. Overheads include non-manufacturing machinery, medical expenses, operational health and safety obligations, packaging, storage facilities and the cost of additional building services [18].

3.6. *OPV module costs*

The total module costs can be expressed in terms of the cost per square metre of production. The OPV production facility start-up and operating costs have been amortised on the basis of the 20 years facility lifetime and 1 m^2/s production rate. These device production costs amount to a total contribution to the OPV module cost of $\$2.25\ m^{-2}$. Similarly, based on the device architecture defined in Section 2.2, the materials costs can also be expressed as a cost per square metre of production taking into account the natural wastage of the fabrication processes. The wastage values have been based on observed experimental procedures for gravure printing and aluminium evaporation processes and have been set as 5% for active layer materials, 5% for anode materials and 500% for cathode materials. Furthermore, additional substrate and encapsulant material is required for the non-active areas of the device (comprising busbars, connectors, etc.), with the photoactive area estimated at 76% of the total module area. The modelled device layout was based on the optimum cell widths determined by Hoppe et al. [46] and is shown in Fig. 4, and the calculated materials costs as a function of module area are outlined in Table 10. The PET substrate and encapsulation represent the greatest cost in a square metre of OPV module and as such present the best opportunity for cost reduction by maximising the active area utilised. Despite the high wastage during deposition (around 500%), the aluminium cathode costs less than $0.01 per square metre, due to the low layer thickness of only 0.1 μm. Chloroform costs are also less than $0.01 per square metre, mostly as a result of low bulk chloroform prices.

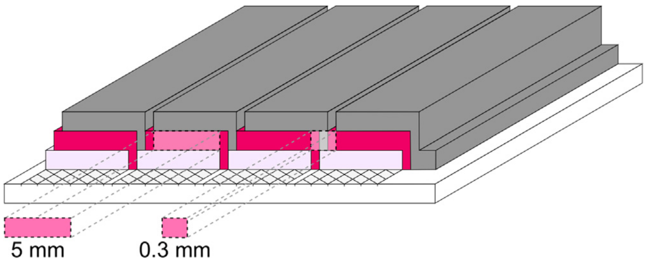

Fig. 4. Modelled module layout illustrating the different layers in the module. The different shaded areas represent the PEDOT:PSS layer (light lilac colour), the active layer (dark pink colour) and the aluminium electrode (mid grey colour). The crosshatched lines represent the silver grid electrode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 10
Material costs in a module (rounded to nearest cent).

Material	Amount (g/m^2)	Cost (\$/m^2)
P3HT (includes 5% wastage)	0.123	0.07
PCBM (includes 5% wastage)	0.123	0.85
PEDOT:PSS (includes 5% wastage)	5.25	1.02
Silver Ink (includes 5% wastage)	<0.001	0.01
Aluminium (includes 500% wastage)	1.62	<0.01
PET (includes 20% non-active area)	1.25 m^2	3.50
Solvent (chloroform)	7.3	<0.01
Acrylic Adhesive	0.023	<0.01
Copper contact	2 pieces	0.02
Total		5.60

Table 11
Module cost range.

Low module cost (\$/m^2)	Calculated module cost (\$/m^2)	High module cost (\$/m^2)
5.50	7.85	10.20

3.7. Total cost of OPV module

The module cost will vary linearly with production yield and thus rather than apply an arbitrary estimate of the yield we have based the calculated module cost on a module production yield of 100%. The calculated total module cost is then \$7.85 m^{-2}. For the purposes of these calculations the error in module cost has been assigned as $\pm$ 30%. Table 11 outlines the upper and lower values for module cost based on this method uncertainty. Unsurprisingly, this result is significantly lower than for current pilot plants [14,15], however, it is also a much lower estimate than predictions based on data from DSC and conventional silicon cells [12]. These contrasting estimates arise from differences in the assumptions and calculation methods. The major differences are that Kalowekamo and Baker assumed the use of 1 μm thick active layers composed of C_{60} and metallophthalocyanines [12] rather than the 100 nm P3HT:PCBM films proposed in this study. They also included the use of an ITO substrate and an additional interfacial layer (4-tertiary butylphenol), hence the overall materials costs were considerably greater than projected in this study. Furthermore, Kalowekamo and Baker based their fabrication on a much slower production rate of approximately 1 m^2 per minute [12], compared with the 1 m^2 per second basis used here.

3.8. Contribution of Components to cost per square metre

Fig. 5A shows the relative contribution of the materials and production costs to the overall total module cost. It is clear from Fig. 5A that the majority of costs per unit area of manufactured OPV module originate from materials, with operating costs contributing a further 25% of the total cost. Fig. 5B shows the breakdown of the materials cost components into the key contributing categories. Interestingly, despite the fact that OPVs are currently fabricated using expensive speciality materials, this analysis shows that once mass manufacture is taken into account these materials contribute less than 20% of the overall materials cost. In fact, the majority of the materials costs originate from the PET substrate and encapsulation, which make up nearly two-thirds of the total module cost and also contribute most to the overall volume and mass of the module.

3.9. Module cost sensitivity

Fig. 6 shows the sensitivity of the costing model to materials prices (both speciality and bulk) as well as to the printing speed of the fabrication facility. The effect of P3HT and PCBM pricing is shown in Fig. 6A and B respectively, where the open circle and square indicate the corresponding current speciality chemical prices of P3HT and PCBM, respectively. These plots highlight that the current price of P3HT is expected to reduce by a greater factor than for the PCBM when bulk production occurs. As such, the PCBM component, while not present in large mass in the modules, is by far the most expensive material by weight and as such the PCBM price moderately influences the module cost. These figures reinforce the fact that basing the cost of OPVs on current speciality chemical prices will necessarily give a high cost for OPV modules, but that when these speciality material costs are calculated under bulk manufacturing conditions then these costs are reduced considerably. Fig. 6C shows the sensitivity of the costing model to the bulk materials prices. It is clear that the PET price has the greatest influence on the module cost, driven by the fact that it is the majority component (by volume and mass) in the OPV module. By contrast, the PEDOT, aluminium and silver prices have a minimal influence on the module cost even when price increases of an order of magnitude are applied.

Fig. 6D illustrates the effect of different production rates on the module cost and reveals that increasing production rates above ~50 m^2/min achieves little gain in overall module cost effectiveness. This threshold value arises from the fact that the capital costs are amortised across the total square metres of module produced. Consequently, these capital costs contribute a lower proportion of the total module cost as higher production rates are achieved. A target production rate of 50–60 m^2/min is not unreasonable [8,21,22], especially when considering that gravure printers used for magazine printing operate at speeds of 100–500 m/min.

The economic model for large-scale production of OPV modules presented in this paper is based on the use of a non-ITO based transparent electrode material such as the widely used PEDOT:PSS/silver grid combination [27–33]. By way of comparison, Fig. 7 shows the effect of using a variety of different ITO anodes instead of the PEDOT:PSS/silver grid system. The use of ITO increases OPV module costs by ~3 times for high resistance ITO and over 30 times for the lowest resistance ITO at current ITO prices [37], corresponding to an ITO based OPV module cost range of \$16–206/m^2 from high to low resistance ITO. A similar result was found by Azzopardi et al. who calculated module costs of \$87–264/m^2 for a cell architecture including ITO [15]. The dramatically increased module costs obtained when incorporating ITO, regardless of the resistance rating, demonstrates the need for a low-cost alternative such as PEDOT:PSS.

Fig. 8 and 9 illustrate the effect of interest rate and payback period on the cost of manufactured OPV modules. As the capital

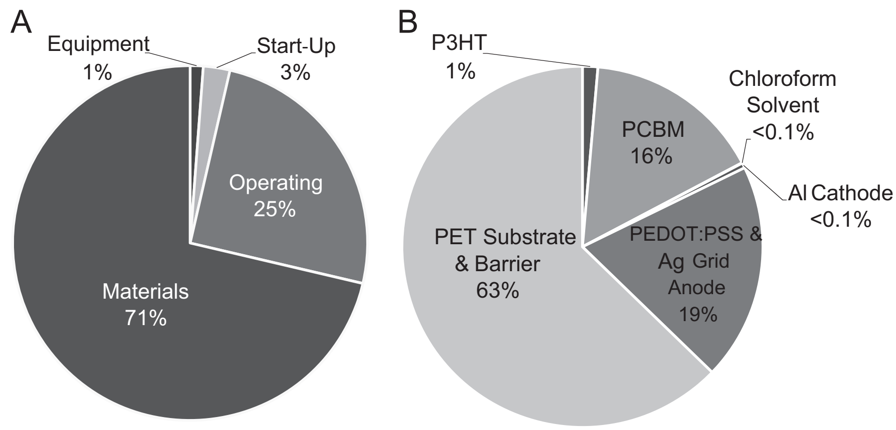

Fig. 5. (A): Contribution of different elements of the manufacturing costs to overall OPV cost. (B): Contribution of the separate materials components to the overall materials cost.

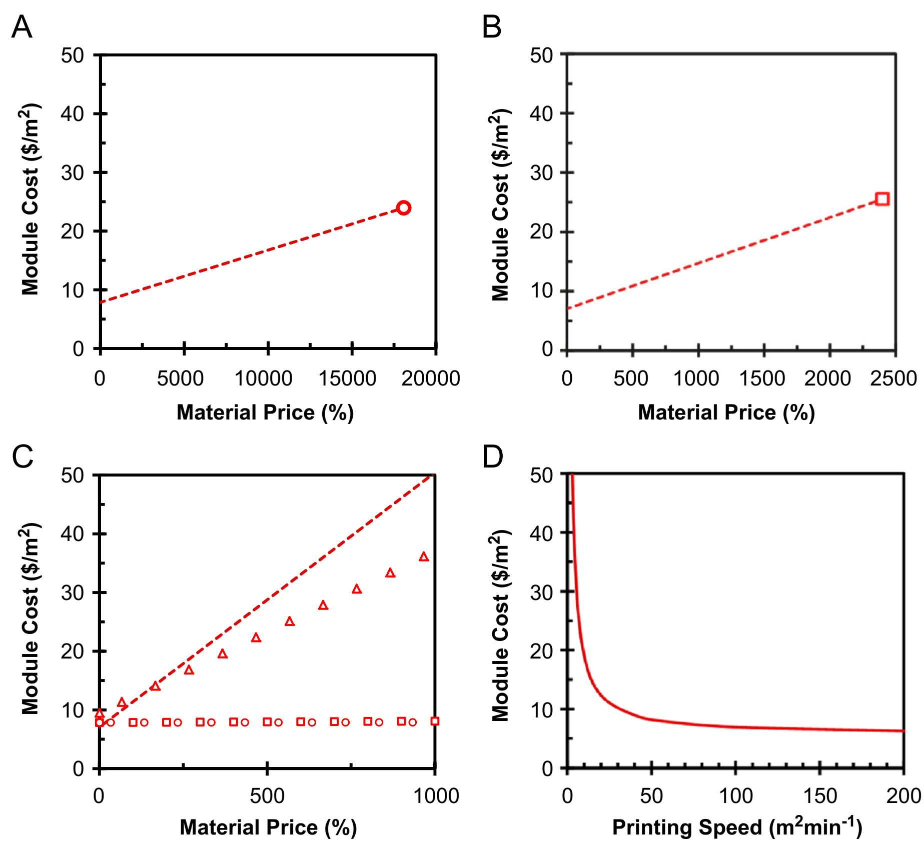

Fig. 6. (A): Sensitivity of module cost to the price of P3HT. The 100% value represents the estimated bulk production price, 0% represents no material cost and the red open circle represents the current (speciality chemical) P3HT price. (B): Sensitivity of module cost to the price of PCBM. The 100% value represents the estimated bulk production price, 0% represents no material cost and the red open circle represents the current (speciality chemical) PCBM price. (C): Sensitivity of module cost to the price of bulk materials: PET (dashed red line), silver (open red circles), aluminium (open red squares) and PEDOT (open red triangles). The 100% value represents the current price of the materials and 0% represents no material cost. All y-axis scales are the same to enable direct comparison between graphs. (D): Sensitivity to module production rate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cost of the manufacturing plant is a small component of the module cost, the sensitivity to the interest rate and payback period is small.

4. Conclusions

We have developed a new economic model for the large scale manufacture of OPV modules incorporating bulk scale manufacture of all of the component materials. The results of this model reveal that the projected cost of large scale manufacture of OPV modules is $\$7.85 \pm 2.35/m^2$, which is considerably lower than typical values currently quoted in the literature. The PET substrate is found to be the major cost in module fabrication; contributing more than half of the overall cost ($\$3.50/m^2$). The operating costs for the fabrication plant then constitute the next largest expense comprising around 25% of the overall OPV module cost.

Using the model, a thorough price sensitivity analysis has been completed. Interestingly, when large scale production of the active materials (P3HT and PCBM) is taken into account, the use of these speciality materials contributes to only a small proportion of the

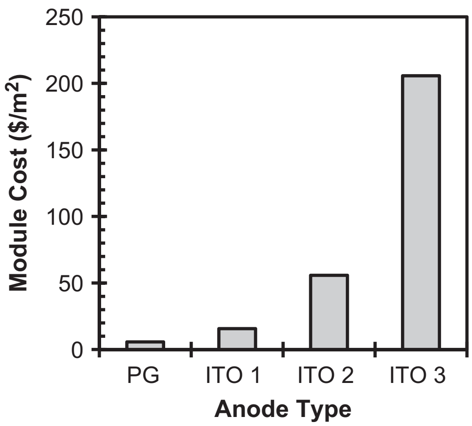

Fig. 7. A comparison of OPV module costs with four different types of anode materials: (1) PEDOT:PSS/Ag grid anode (PG), (2) ITO anode with sheet resistance of 400 Ω/sq (ITO 1), (3) ITO anode with sheet resistance of 60 Ω/sq (ITO 2) and (4) ITO anode with sheet resistance of 6 Ω/sq (ITO 3).

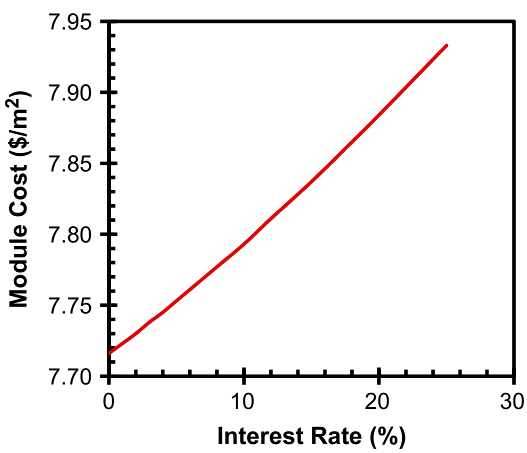

Fig. 8. Sensitivity of module cost to interest rate.

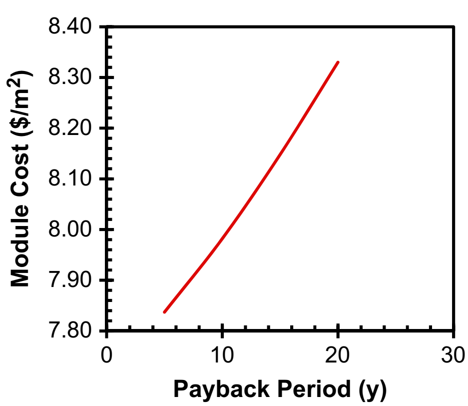

Fig. 9. Sensitivity of module cost to payback period.

module cost and this proportion is largely insensitive to small price changes of these materials. In addition, the module cost is not strongly affected by increased polymer, cathode or anode costs even for price increases of 1000%. The calculations assume the use of a conducting polymer/ metal grid anode rather than ITO; substituting ITO into the calculations leads to increases in the module cost of up to 3600%. Significantly, we predict that current reel-to-reel production rates, if adapted to OPV production are adequate to minimise production costs, with module costs not markedly decreasing for rates above 50 m^2/min. Overall this work clearly demonstrates that OPV modules can be produced at much lower cost on a commercial scale than currently predicted in the literature.

The results highlight the cost potential of OPV technology and illustrate the likely beneficial results of future work towards scaling-up polymer and fullerene production, developing techniques with moderate production speeds, and using ITO replacements such as PEDOT/metallic grid combinations. As such, the results of this model provide a sound basis for future feasibility studies into the use of OPV as a commercially viable energy source. Further work determining complete installation costs and the levelised cost of electricity is being undertaken based on these results.

Acknowledgements

The University of Newcastle is gratefully acknowledged for Ph.D. scholarships (CM, MW). This work was performed in part at the Materials node of the Australian National Fabrication Facility. A company established under the National Collaborative Research Infrastructure Strategy to provide nano and microfabrication facilities for Australia's researchers.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.solmat.2013.07.041.

References

[1] M. Romero, A. Steinfeld, Concentrating solar thermal power and thermochemical fuels, Energy & Environmental Science 5 (2012) 9234–9245.
[2] A. Sumper, M. Robledo-García, R. Villafáfila-Robles, J. Bergas-Jané, J. Andrés-Peiró, Life-cycle assessment of a photovoltaic system in Catalonia (Spain), Renewable & Sustainable Energy Reviews 15 (2011) 3888–3896.
[3] M. Grätzel, Recent advances in sensitized mesoscopic solar cells, Accounts of Chemical Research 42 (2009) 1788–1798.
[4] B. Kippelen, J.-L. Brédas, Organic photovoltaics, Energy & Environmental Science 2 (2009) 251–261.
[5] B.A. Andersson, S. Jacobsson, Monitoring and assessing technology choice: the case of solar cells, Energy Policy 28 (2000) 1037–1049.
[6] K.M. Coakley, M.D. McGehee, Conjugated polymer photovoltaic cells, Chemistry of Materials 16 (2004) 4533–4542.
[7] M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (version 38), Progress in Photovoltaics: Research and Applications 19 (2011) 565–572.
[8] F.C. Krebs, Fabrication and processing of polymer solar cells: a review of printing and coating techniques, Solar Energy Materials and Solar Cells 93 (2009) 394–412.
[9] P. Kopola, T. Aernouts, R. Sliz, S. Guillerez, M. Ylikunnari, D. Cheyns, M. Välimäki, M. Tuomikoski, J. Hast, G. Jabbour, R. Myllylä, A. Maaninen, Gravure printed flexible organic photovoltaic modules, Solar Energy Materials and Solar Cells 95 (2011) 1344–1347.
[10] G. Dennler, C.J. Brabec, Socio-economic impact of low-cost PV technologies, in: C. Brabec, V. Dyakonov, U. Scherf (Eds.), Organic Photovoltaics, Wiley-VCH, Weinheim, Germany, 2008, pp. 531–567.
[11] G. Dennler, M.C. Scharber, C.J. Brabec, Polymer-fullerene bulk-heterojunction solar cells, Advanced Materials 21 (2009) 1323–1338.
[12] J. Kalowekamo, E. Baker, Estimating the manufacturing cost of purely organic solar cells, Solar Energy 83 (2009) 1224–1231.
[13] A.L. Roes, E.A. Alsema, K. Blok, M.K. Patel, Ex-ante environmental and economic evaluation of polymer photovoltaics, Progress in Photovoltaics: Research and Applications 17 (2009) 372–393.
[14] F.C. Krebs, T. Tromholt, M. Jørgensen, Upscaling of polymer solar cell fabrication using full roll-to-roll processing, Nanoscale 2 (2010) 873–886.
[15] B. Azzopardi, C.J.M. Emmott, A. Urbina, F.C. Krebs, J. Mutale, J. Nelson, Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment, Energy & Environmental Science 4 (2011) 3741–3753.
[16] C. Powell, Y. Lawryshyn, T. Bender, Using stochastic models to determine financial indicators and technical objectives for organic solar cells, Solar Energy Materials and Solar Cells 107 (2012) 236–247.

[17] T.D. Nielsen, C. Cruickshank, S. Foged, J. Thorsen, F.C. Krebs, Business, market and intellectual property analysis of polymer solar cells, Solar Energy Materials and Solar Cells 94 (2010) 1553–1571.
[18] M.S. Peters, K.D. Timmerhaus, R.E. West, Plant Design and Economics for Chemical Engineers, fifth ed., McGraw-Hill Publishing, New York, USA, 2003.
[19] R.K. Sinnott, J.M. Coulson, J.F. Richardson, Chemical Engineering Design, vol. 6, Elsevier Butterworth-Heinemann Publishing, Oxford, USA, 2005.
[20] F.C. Krebs, S.A. Gevorgyan, J. Alstrup, A roll-to-roll process to flexible polymer solar cells: model studies, manufacture and operational stability studies, Journal of Materials Chemistry 19 (2009) 5442–5451.
[21] R. Kukla, E. Josephson, Vacuum web coating—state of the art and potential for electronics, Proceedings of the IEEE 93 (2005) 1483–1490.
[22] F. Jakubka, M. Heyder, F. Machui, J. Kaschta, D. Eggerath, W. Lövenich, F. C. Krebs, C.J. Brabec, Determining the coating speed limitations for organic photovoltaic inks, Solar Energy Materials and Solar Cells 109 (2013) 120–125.
[23] C.J.M. Emmott, A. Urbina, J. Nelson, Environmental and economic assessment of ITO-free electrodes for organic solar cells, Solar Energy Materials and Solar Cells 97 (2012) 14–21.
[24] R. Andriessen, Y. Galagan, J.-E. Rubingh, N. Grossiord, P. Blom, J.M. Kroon, S. Veenstra, W. Verhees, L. Slooff, P. Pex, Towards low cost, efficient and stable organic photovoltaic modules, 27th European Photovoltaic Solar Energy Conference and Exhibition, 24–28 Sep 2012, Frankfurt, Germany.
[25] T. Aernouts, P. Vanlaeke, W. Geens, J. Poortmans, P. Heremans, S. Borghs, R. Mertens, R. Andriessen, L. Leenders, Printable anodes for flexible organic solar cell modules, Thin Solid Films 451–452 (2004) 22–25.
[26] T. Ameri, G. Dennler, C. Waldauf, H. Azimi, A. Seemann, K. Forberich, J. Hauch, M. Scharber, K. Hinger, C.J. Brabec, Fabrication, optical modeling, and color characterization of semitransparent bulk-heterojunction organic solar cells in an inverted structure, Advanced Functional Materials 20 (2010) 1592–1598.
[27] B. Winther-Jensen, F.C. Krebs, High-conductivity large-area semi-transparent electrodes for polymer photovoltaics by silk screen printing and vapour-phase deposition, Solar Energy Materials and Solar Cells 90 (2006) 123–132.
[28] Y. Galagan, J.E.J.M. Rubingh, R. Andriessen, C.C. Fan, P.W.M. Blom, S.C. Veenstra, J.M. Kroon, ITO-free flexible solar cells with printed current collecting grids, Solar Energy Materials and Solar Cells 95 (2011) 1339–1343.
[29] F.C. Krebs, All solution roll-to-roll processed polymer solar cells free from indium-tin-oxide and vacuum coating steps, Organic Electronics 10 (2009) 761–768.
[30] M. Manceau, A. Dechan, M. Jørgensen, F.C. Krebs, ITO-free flexible polymer solar cells: from small model devices to roll-to-roll processed large modules, Organic Electronics 12 (2011) 566–574.
[31] M. Strange, D. Plackett, M. Kaasgaard, F.C. Krebs, Biodegradable polymer solar cells, Solar Energy Materials and Solar Cells 92 (2008) 805–813.
[32] K. Tvingstedt, O. Inganäs, Electrode grids for ITO free organic photovoltaic devices, Advanced Materials 19 (2007) 2893–2897.
[33] S.C. Veenstra, J.M. Kroon, ITO-free flexible organic solar cells with printed current collecting grids, Solar Energy Materials and Solar Cells 95 (2011) 1339–1343.
[34] M. Kaltenbrunner, M.S. White, E.D. Głowacki, T. Sekitani, T. Someya, N. S. Sariciftci, S. Bauer, Ultrathin and lightweight organic solar cells with high flexibility, Nature Communications 3 (2012) http://dx.doi.org/10.1038/ncomms1772 (article no. 770).
[35] Kitco, 〈http://www.kitco.com〉 (accessed July 2011).
[36] London Metal Exchange 〈http://www.lme.com/〉, (accessed July 2011).
[37] Alibaba 〈http://www.alibaba.com/〉, (accessed Dec 2012).
[38] ICIS 〈http://www.icis.com/〉, (accessed July 2011).
[39] T.P. Osedach, T.L. Andrew, V. Bulovi´c, Effect of synthetic accessibility on the commercial viability of organic photovoltaics, Energy & Environmental Science 6 (2013) 711–718.
[40] Australian Government Fair Work Ombudsman, 〈http://www.fairwork.gov.au/awards/a-z-of-modern-awards/pages/default.aspx〉, (accessed July 2011).
[41] M. Bazilian, I. Onyeji, M. Liebreich, I. MacGill, J. Chase, J. Shah, D. Gielen, D. Arent, D. Landfear, S. Zhengrong, Re-considering the economics of photovoltaic power, Bloomberg New Energy Finance White Paper, (2012).
[42] M. Landman, H. Görls, S. Lotz, Chromium and tungsten carbene complexes of thieno[3,2-b]thiophene, European Journal of Inorganic Chemistry 1 (2001) 233–238.
[43] R.D. McCullough, R.D. Lowe, M. Jayaraman, D.L. Anderson, Design, synthesis, and control of conducting polymer architectures: structurally homogeneous poly(3-alkylthiophenes), Journal of Organic Chemistry 58 (1993) 904–912.
[44] R.S. Loewe, S.M. Khersonsky, R.D. McCullough, A simple method to prepare head-to-tail coupled, regioregular poly(3-alkylthiophenes) using grignard metathesis, Advanced Materials 11 (1999) 250–253.
[45] J.C. Hummelen, B.W. Knight, F. LePeq, F. Wudl, J. Yao, C.L. Wilkins, Preparation and characterization of fulleroid and methanofullerene derivatives, Journal of Organic Chemistry 60 (1995) 532–538.
[46] H. Hoppe, M. Seeland, B. Muhsin, Optimal geometric design of monolithic thin-film solar modules: architecture of polymer solar cells, Solar Energy Materials and Solar Cells 97 (2012) 119–126.