



A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions

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ARTICLE INFO

Article history:

Received 17 June 2010

Received in revised form

12 August 2010

Accepted 17 August 2010

Keywords:

Life cycle analysis

Polymer solar cells

Roll-to-roll coating

Flexible substrates

ABSTRACT

A life cycle analysis was performed on a full roll-to-roll coating procedure used for the manufacture of flexible polymer solar cell modules. The process known as ProcessOne employs a polyester substrate with a sputtered layer of the transparent conductor indium-tin-oxide (ITO). The ITO film was processed into the required pattern using a full roll-to-roll process, employing screen printing of an etch resist and then applying etching, stripping, washing and drying procedures. The three subsequent layers; ZnO, P3HT:PCBM and PEDOT:PSS were slot-die coated and the silver back electrode was screen printed. Finally the polymer solar modules were encapsulated, using a polyester barrier material. All operations except the application of ITO were carried out under ambient conditions. The life cycle analysis delivered a material inventory of the full process for a module production, and an accountability of the energy embedded both in the input materials and in the production processes. Finally, upon assumption of power conversion efficiencies and lifetime for the modules, a calculation of energy pay-back time allowed us to compare this roll-to-roll manufacturing with other organic and hybrid photovoltaic technologies. The results showed that an Energy Pay-Back Time (EPBT) of 2.02 years can be achieved for an organic solar module of 2% efficiency, which could be reduced to 1.35 years, if the efficiency was 3%.

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1. Introduction

Polymer solar cells have been heralded as a technology that can deliver electricity at very low cost. This generally accepted postulate has been left unchallenged and it is based on the common attributes known for plastic or polymer based materials. When industry replaces a material (e.g. wood or metal) by a plastic material, this is often done because it leads to cost reduction with little or no sacrifice in performance as perceived by the end user. The cost reduction is most often achieved through lower weight, higher manufacturing speed, lower thermal budgets and often less demanding and less complex manufacturing equipment. When considering the traditional solar cell manufacturing business, this is for first generation solar cells based on wafer processing which has been optimized for manufacture of miniature integrated circuits. It is hardly surprising that it is unsuitable for large area applications, which is what photovoltaic applications demand and this fact has been viewed by many as one of the reasons that the learning curve for

crystalline silicon has been too slow for the technology to claim a significant share of renewable energy production. The fact that polymer solar cells can potentially be manufactured using high speed roll-to-roll processing on light weight flexible substrates is what has been viewed as the chief asset by which polymer solar cells offer a convincing solution to the problem of scalability that all other solar cell technologies are faced with. Such an opportunity naturally warrants further examination; however, there are for the time being scarce scientific reports in large area production of these polymer solar cells [1–4] and by roll-to-roll methods [5–7]; that it is not to say that they have not taken place, but companies use to hold this information as confidential. While the critics argue that it is not useful to prepare a very scalable solar cell in high volume if it is poorly performing in terms of efficiency and stability, some breakthroughs have been recently achieved: power conversion efficiencies up to 8.13% [8,9], and lifetimes of many years have been proven [10,11].

The environmental impact of energy production processes ultimately affects the cost of energy, and therefore it is highly important to perform careful Life Cycle Assessments (LCA) of any source of energy. The LCA must always serve as a basis when taking on optimistic views of how a novel energy technology impacts the environment and how it might acquire a share of the

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produced electricity and influence the final market cost of electricity per kWh.

It has been generally confirmed by previous LCA studies that renewable sources of electricity, such as photovoltaic technologies, have low values for the CO₂ equivalent emission figures per kWh. For photovoltaic technologies, this ranges between 20 and 37 g per kWh, and thus compares very favorably to coal (900 g), natural gas combined cycle (439 g) and even nuclear energy (40 g), which has been touted as the cleanest technology. In order to compare different energy technologies, a useful parameter is the Energy Pay-Back Time (EPBT), defined as the time required for an energy system to generate the amount of energy consumed during its construction and decommissioning phases, including the material processing from scratch. The EPBT has been thoroughly investigated for all PV technologies already on the market, and ranges between 4.12 and 0.73 years. The most significant values are the following: mono-Si: 4.12 to 2.68 years, depending on a range of power conversion efficiencies (11.8–14%) given for commercial modules, [12–14]; poly-Si, 2 years for 13% efficiency [13,15]; amorphous-Si, 1.13 years for 7% efficiency [16]; CIS, 2.26–2.2 years for 8.9–11% efficiency [14,17], and CdTe, 1.61–0.73 years for 11–13% [17,18]. Other hybrid and organic technologies have also been studied, delivering a broad set of EPBT figures ranging between 5 and 0.6 years. A more detailed discussion will be given below since different approaches have been accomplished for the calculation of environmental impact and costs for laboratory fabrication procedures [19] and for larger scale module manufacturing [20–22]. A detailed material inventory, also useful to identify possible bottlenecks for massive production, has been accomplished for ProcessOne.

The chemical synthesis of conjugated polymers suitable for efficient light harvesting (good absorption and bandgap tuning), the exploitation of self-assembling properties of polymers and blends of polymers with nanoparticles during the manufacturing process, and the optimal contact for selective electrodes in serial-

connected cells for a monolithic module design, implies a huge scientific and technological research effort that could ultimately yield a simple processing method, capable of a large scale industrial manufacture of efficient and stable organic photovoltaic modules, by means of well-known coating printing processes [23–25], and flexible packaging industry knowledge [26,27]. This processing method or “package” technology, such as ProcessOne, will also have the capability of becoming a real horizontal technology transfer vector for massive production in developing countries, where cheap electricity from a reliable and environment-friendly renewable source of electricity is strongly needed, especially for rural livelihoods [28].

In this study, we present a life cycle analysis for ProcessOne, which is one of the first reported industrial manufacturing processes leading to flexible polymer solar cell modules that have been demonstrated and for which manufacturing details are available. We seek to establish the parameters that are critical for the beneficial use of polymer solar cells in society and to firmly demonstrate where the potential of the polymer solar cell technology is.

2. Experimental procedure and methodology

2.1. Manufacture of polymer solar modules

The manufacture of polymer solar cells by ProcessOne was made following the six steps shown in Fig. 1. A roll of PET substrate, which has been sputtered with indium-tin-oxide (ITO), is patterned with a curable etch resist printing procedure. On the patterned ITO, three layers were deposited by slot-die coating: ZnO, P3HT:PCBM and PEDOT:PSS, and finally, on top, the back electrode constituted by a silver mesh is screen printed. The encapsulation of the module is made using a polyester barrier material by a roll-to-roll lamination.

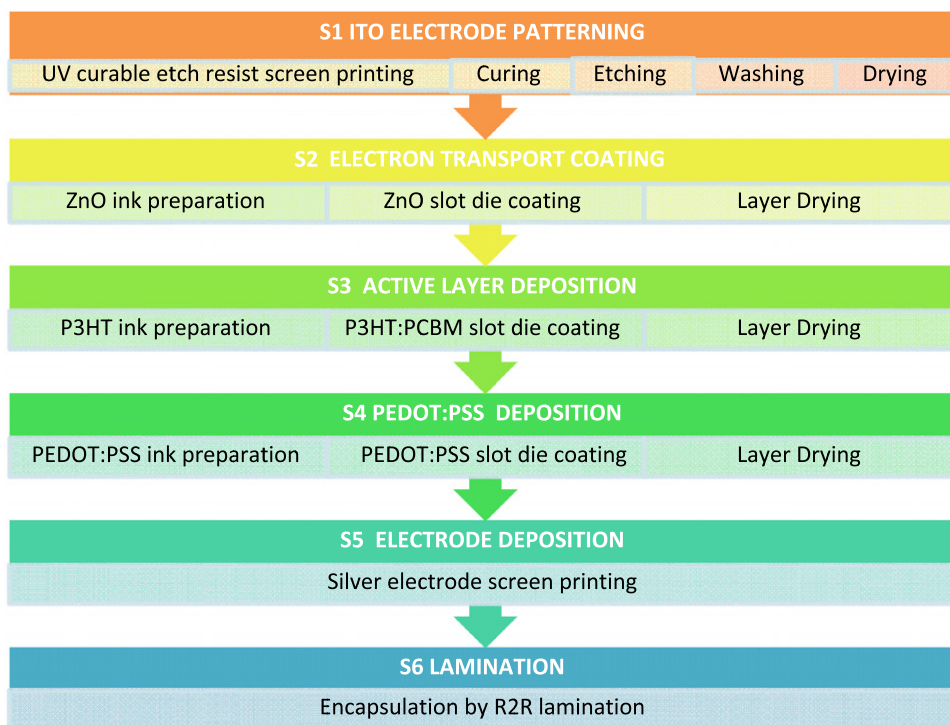


Fig. 1. Steps and substeps during the ProcessOne PV module processing.

In Fig. 1, the main fabrication processes and subprocesses are presented, the following paragraphs describe in detail each of the six steps based on previously reported studies [29,30].

Step 1: ITO electrode patterning

The most commonly employed transparent conductor is indium-tin-oxide (ITO), which is commercially available on flexible PET foil. In this case, a 130 μm PET substrate was employed with a fully covering layer of ITO with a sheet resistivity of $60 \Omega/\square$ and a thickness of 90 nm, which had been sputtered using a vacuum roll-to-roll process. Due to the relatively high sheet resistivity of the ITO it is necessary to pattern the ITO, so that smaller cells can be connected in series. This involves the screen printing in a Klemm printer line of an etch resist and UV curable ink onto the ITO-covered PET material, with the desired ITO pattern. This Klemm line comprises unwinder, flat bed screen printer, UV-curing oven and rewinder.

The flat bed screen printer is operated at 800 prints/h, corresponding to a web speed of 3.3 m/min. The screen printing of the etch resist was carried out directly on the PET-ITO substrate as received from the manufacturer. Then, the curing of the etch resist substance was done to protect the ITO that should not be etched, in a UV curing lamp with the conditions shown in Table 2. The ITO was then etched using CuCl_2 (aq) followed by washing, stripping – the etch resist – and drying. The processing speed during etching, stripping and drying of the ITO was also 198 m/h. Conditions and material inventory for screen printing, curing and etching are shown in Tables 1–3.

Step 2: Electron transport layer coating

Three processes comprise this step. First the ZnO ink which consists of ZnO nanoparticles was prepared. ZnO nanoparticles were synthesized by caustic hydrolysis of $\text{Zn}(\text{OAc})_2 \cdot 2\text{H}_2\text{O}$, heated and stabilized with methoxyethoxyacetic acid (MEA) [31], and mixed with acetone, to give ZnO nanoparticles in acetone. This stock solution was diluted with to give the final ink that was microfiltered through a 0.45 μm Teflon filter immediately prior to coating. The concentration of ZnO nanoparticles in the final coating ink was 30 mg/ml (see Table 4).

The slot-die coating was performed on a BC30 basecoater from Solar Coating Machinery (Germany) described in Table 5. It was first necessary to clean the ITO substrate by passage through the system using corona treatment, web cleaning and washing using isopropanol followed by drying at 140 °C. Each motif was labeled on the backside with the date and a unique number for later identification. The typical coating speed during ZnO deposition was 120 m/h. The material was again dried at temperatures of up to 140 °C with a residence time in the oven of around 1 min. This procedure polymerizes the film containing the ZnO nanoparticles and gives insoluble films of zinc oxide. The wet layer thickness was 3.125 μm and the dry layer thickness was 23 nm. All conditions are shown in Table 5.

Step 3: Active layer deposition

The ink for the active layer was prepared by dissolving commercially purchased P3HT (18–24 mg/ml) and PCBM (16–22 mg/ml) in chlorobenzene at 120 °C for 3 h. The ratio between P3HT and PCBM was typically 10:9. The blend was coated on the substrate with the ZnO layer, at a web speed of 1.4 m/min, using 2 mL per linear meter, resulting in 4.85 μm layer of wet thickness, which leads to a final dry layer thickness of 127 nm. (See Tables 6 and 7).

Step 4: PEDOT:PSS deposition

For the ink preparation PEDOT:PSS was purchased as EL-P 5010 from Agfa and was diluted slowly with isopropanol using stirring until a solution viscosity of 270 mPa s was obtained. The wetting of P3HT:PCBM by PEDOT:PSS is not very good and because the use of corona treatment is not possible, it was useful to mix isopropanol into the PEDOT:PSS and also wet the active

Table 1

Screen printing of UV curable substance conditions and material inventory for 1 m² processed surface.

Conditions	
Speed	198 m/h
Working printer power	60,000 W
Equipment	
Description	Klemm line printer: unwinder, flat bed screen printer, UV-curing oven and rewinder
Maximum printer power	150,000 W
Material inventory	
UV curable ink	3.28 g

Table 2

Curing process conditions and material inventory for 1 m² processed surface.

Conditions	
Speed	198 m/h
Working lamp power	15,000 W
Equipment	
Description	The etch resist substance, deposited previously by screen printing, is hardened in a UV-curing oven inside the printer. UV lamp includes also an air-fan to cool the water cooling for the lamp.
Maximum lamp power	15,000 W (including air-fan cooler power)

Table 3

Etching process conditions and material inventory for 1 m² processed surface.

Conditions	
Speed	198 m/h
Working etcher power	10,000 W
Working dryer power	20,000 W
Working air-fan power	20,000 W
Equipment	
Description	R2R etching machine: etching, stripping and washing baths.
Maximum etcher power	100,000 W
Maximum dryer power	20,000 W
Maximum air-fan power	20,000 W
Material inventory	
CuCl_2	0.25 g
Water	0.52 L
NaOH	1.66 g
Demineralised water	0.21 L

Table 4

ZnO ink preparation equipment and material inventory for 1 m² processed surface.

Conditions	
Working heater power	150 W
Equipment	
Maximum heater power	1000 W
Material inventory	
$\text{Zn}(\text{OAc})_2$	0.40 g
KOH	0.20 g
MeOH	1.6 mL
Acetone	3.32 mL
MEA	0.04 g

layer with isopropanol, immediately before the slot-die coating head as described earlier [32]. The devices are also prewashed with isopropanol during coating because this procedure results in much smoother films and better interfaces between the active

Table 5

ZnO slot-die coating and drying conditions and material inventory for a 1 m² processed surface.

Conditions	
Speed	120 m/h
Web tension	80–90 N
Drying temperature	140 °C
Working corona treater power	1500 W
Working slot die power	2500 W
Working oven power	12,000 W
Equipment	
Description	BC30 basecoater comprising: unwinder, corona treater, edge guide, double faced contact cleaning, antistatic system, coating roller, ink jet labeling printer, oven, cooling roller and winding station.
Maximum corona treater power	1500 W
Maximum slot die coater power	2500 W
Maximum oven power	40,000 W
Material inventory	
ZnO ink	3.27 mL
Isopropanol (washing)	25.77 g

Table 6

Active layer blend preparation and material inventory for 1 m² processed surface.

Conditions	
Heating temperature	120 °C
Equipment	
Working heater power	100 W
Material inventory	
P3HT	0.1 g
PCBM	0.08 g
Chlorobenzene	6.56 mL

Table 7

Active layer deposition and material inventory for 1 m² processed surface.

Conditions	
Speed	84 m/h
Working slot die power	2500 W
Working oven power	12,000 W
Equipment	
Description	BC30 basecoater comprising: unwinder, corona treater, edge guide, double faced contact cleaning, antistatic system, coating roller, ink jet labeling printer, oven, cooling roller and winding station.
Maximum slot die power	2500 W
Maximum oven power	40,000 W
Material inventory	
Active layer ink	6.56 mL

layer and the PEDOT:PSS layer. The coating was performed at low speed (see Table 8), in order to ensure proper drying of the thick PEDOT:PSS layer due to the short available drying length of 1 m. The wet thickness of this layer was 75 µm and had dry layer thickness of 20 µm.

Step 5: Back electrode deposition

The screen printing of the silver back electrode was carried out on a flat bed roll-to-roll screen printer AT701 from Alraun Technik (Germany). The screens were mounted with a 120 mesh screen for printing the silver paste. The effective web speed was 1 m/min, which is intentionally low due to the relatively short drying length for the oven (120 cm). The residence time in the oven was

Table 8

PEDOT:PSS preparation, slot-die coating conditions and material inventory for 1 m² processed surface.

Conditions	
Stirrer	50 W
Speed	18 m/h
Working slot die power	2500 W
Working oven power	12,000 W
Equipment	
Description	BC30 basecoater comprising: unwinder, corona treater, edge guide, double faced contact cleaning, antistatic system, coating roller, ink jet labeling printer, oven, cooling roller and winding station.
Maximum slot die coater power	2500 W
Maximum oven power	40,000 W
Material inventory	
Isopropanol	14.75 g
PEDOT:PSS	29.51 g
Isopropanol (washing)	25.77 g
PEDOT:PSS ink	44.26 g

Table 9

Silver electrode screen printing conditions and material inventory for 1 m² processed surface.

Conditions	
Speed	60 m/h
Residence time in oven	72 s
Drying temperature	130 °C
Working printer power	15,000 W
Equipment	
Description	Alraun printer comprising unwinder, metering wheel, positioning camera, vacuum table, screen printer (AT701), hot air oven, transport rollers, dancing tensioning roller and rewinder
Maximum printer power	38,000 W
Material inventory	
Silver ink (PV 410)	19.67 g

Table 10

Lamination conditions and material inventory for 1 m² of processed surface.

Conditions	
Speed	120 m/h
Working laminator power	1500 W
Equipment	
Description	Laminator comprising unwinder, edge guide and cutting table, laminator, laminate unwinder, longitudinal cutting knives and rewinder.
Maximum laminator power	1500 W
Material inventory	
3 M 467 MPF	50.60 g
PET barrier	72.75 g

72 s and the drying temperature was 130 °C. The positioning followed a hole that was punched during screen printing of the etch resist for the ITO. The system is fully automated and controlled by a computer. The foil was moved forward at a speed of 1 m/min, until the register mark was reached. The foil was then fixed on the vacuum table and the motif was printed followed by moving the foil to the next motif. (Table 9).

Step 6: Lamination

Complete lamination of the modules was carried out in several steps that employed the laminator described in Table 10. Firstly,

the adhesive was laminated onto the barrier foil. The width of the barrier foil, purchased from Amcor Flexibles was 305 mm, while the width of the lined adhesive (3 M 467 MPF) was 298 mm in order to avoid adhesive build-up on the laminating rubber rollers in case of slight misalignment between the adhesive and the barrier foil. The barrier material with the lined adhesive could then be cut to a width of 250 mm for the backside in order to enable lamination of the active areas, while exposing some of the silver bus bars for electrical connections during roll-to-roll IV-testing. After application of the adhesive onto the barrier foil, it was laminated onto the unencapsulated solar cell material, on both sides of the devices.

2.2. Methodology and scope of the life cycle assessment for ProcessOne

Using the manufacture process described above, we have proceeded following the standard approach of Life Cycle Assessment [12,33]. The scope and boundary of each analysis has to be clearly stated. In our study we have focused on three main stages: (1) material inventory for the production of an organic solar module, including solvents and other materials not present in the final module, (2) energy embedded in the manufacture of materials from raw materials to an initial input into the manufacture machinery, and (3) energy embedded in the direct process. As it is known, stages (1) and (3) are strongly dependent on the manufacturing process, but stage (2) can benefit from our own previous studies on laboratory scale production, using very similar materials as active layers and electrodes included in the device [19], and also from available inventory data-bases [15,34,35]. When a particular chemical process is not available, the use of grouping in similar chemical production categories has been useful in order to provide the figures needed for the LCA calculation.

Decommissioning procedures have not been taken into account in this LCA calculation. It is still a preliminary stage of deployment of the technology and a lack of solid knowledge of the recycling procedures for some of the materials included in the final organic module makes it unreliable to perform a calculation of the energy embedded in the decommissioning steps. Nevertheless, the recycling of some materials (especially solvents such as methanol) during manufacturing following ProcessOne has been taken into account in the calculations. Balance of System (BOS) analysis is also outside the purpose of the LCA calculation presented in this article; therefore, the comparison with other PV technologies is performed at a module level.

In order to compare with other PV technologies, further calculation stages beyond the three described above have to be performed. The functional unit for the ProcessOne organic modules calculation has been the total processed area per 1 m of processed foil (305 mm width, 3050 cm² processed area), by working with this unit, or often converting it to a more standard 1 m² of processed surface, a stable power conversion efficiency has to be assumed in order to obtain a final value for total energy embedded per amount of produced energy in standard AM1.5G conditions. Also corrections that take into account the area of the active area and not the area of the whole module for power conversion efficiency calculation will improve the figures of an LCA. If the lifetime of the module is also known, a further calculation for a fixed time window can be performed; this is necessary in order to properly compare PV technologies which have already demonstrated a very reliable output for more than 25 years, like mono-Si, multi-Si or some thin film technologies, which have lifetimes well above this figure. During the lifetime of a single conventional mono-Si panel, the replacement of several

organic modules should be taken into account, since lifetimes are still below the objective of 5 years described in the European PV Technology Platform Report [36]. Most often, all PV technologies are compared in Standard AM1.5G conditions for which peak values of manufacturers are provided when a module is sold. Taking into account other illumination conditions, like diffuse light, albedo, or artificial light for which it is well known that organic technologies perform comparatively better than conventional inorganic technologies, the LCA results would be better than for an AM1.5G. The comparison with other hybrid and organic technologies would not be affected since all of them benefit from this fact. Finally, in order to calculate an environmental impact more focused on emissions of CO₂ equivalent, a further assumption has to be taken into account: an energy mix for the geographical location of the manufacturing process should be selected. For ProcessOne, we have used the energy mix for Denmark (420.88 g-eqCO₂/kW_{el}) in 2008, [37] which includes an important share for renewable energy (20% in 2008), since Denmark is leader in wind energy and has one of the cleanest energy mix in the European Union and a very low emission factor [38,39]. With these data, and for the energy values calculated as explained in LCA stages, two emission factors for ProcessOne can be calculated.

3. Results and discussion

3.1. ProcessOne life cycle analysis

In the following paragraphs, we present the results for the LCA of the ProcessOne manufacture described in Section 2, which can be summarized as: polymeric modules on flexible PET substrate, ITO and Ag electrodes with intermediate layers of ZnO, P3HT:PCBM as active layer and PEDOT, subsequently coated between both electrodes.

3.1.1. Raw materials

The life cycle of the raw materials used in the preparation of the cell must be analyzed in order to calculate the full embedded energy per square meter of module.

It includes:

- PET substrate.
- Electrodes: front ITO transparent oxide electrode and silver back electrode.
- Front electron transport layer: ZnO nanoparticles.
- Active layer: blend of polymer and fullerene derivative, in this case P3HT:PCBM blend was used.
- PEDOT:PSS layer as hole conductor.
- Encapsulation: adhesive and barrier foil.

3.1.1.1. Energy requirements for chemical synthesis steps.

Estimation of energy requirements in the production of special chemicals is quite complex, since information on such production processes is scarce. Moreover many of the chemical processes presented in this work are not yet in a full production scale. The estimation of energy in chemical synthesis for most of components was accomplished in previous works [19,40]. The processing energy for all listed components is presented in Table 11.

3.1.2. Material inventory

Material inventory is the amount of raw materials used to manufacture a functional unit of PV module. This calculation is the starting point for obtaining the energy embedded in a defined surface of the active solar cell, plus the non-active surface which

Table 11

Cumulative energy requirements for raw materials production.

Raw materials inventory	Thermal energy (kJ _{th})	Electrical energy (kJ _{el})	Refs.
PET (1 kg)	51,314.56	5813.05	PET film [35]
ITO (1 m ²)	55.29	88,632.86	[19], Calculated
NaOH (1 kg)	8088.00	4175.50	[35]
Demineralised water (1 m ³)	-	1080.00	[41]
KOH (1 kg)	8088.00	4175.50	[35]
MeOH (1 kg)	160.00	12,705.53	[42]
Acetone (1 kg)	49,552.00	1589.00	[35]
Isopropanol	160.00	12,705.53	[42]
MEA (1 kg)	33,520.00	14,665.00	[35]
P3HT 99%HT (1 kg)	1148.03	131.07	[19]
PCBM (1 kg)	6769.93	908.77	[19]
Chlorobenzene (1 kg)	48,552.00	1410.50	Grouping benzene and Cl ₂ [35]
Adhesive resin (1 kg)	69,288.00	3055.50	Considered as PET [35]
Barrier resin (1 kg)	51,314.56	5813.05	[35]

contributes to the total module surface. The subsequent energy calculations will take into account this material inventory. Also, some materials used in PV technologies are scarce and this fact could become an important problem for a large scale deployment of a particular PV technology, the material inventory is useful in order to identify possible bottlenecks for this up-scaling in the production.

ProcessOne allows to prepare organic solar modules of 16 stripes of 13 mm width and 562 cm² of processed area. In order to compare well with different technologies, we need the material and energy requirements for 1 m², where 67% of the area is active; we use this correction factor for the calculated material inventory of the final organic module.

3.1.3. Embedded energy in material processing

Once the material inventory and calculation of embodied energy in raw materials production have been accomplished, the embodied energy for input materials can be obtained as shown in Table 13.

Finally, using the energy input of the cell fabrication method described in Section 2.1, the energy input required for the raw material processing, given in Section 3.1.1, and the material inventory indicated in Table 12, the embedded energy per square meter of solar module can be obtained. Such embodied energy will be used for the calculation of the energy payback time and at the same time, for comparison with other photovoltaic technologies.

As it is recommended in the reference literature, all the energy results are converted to Equivalent Primary Energy¹ (EPE) per surface in order to make easier the comparison with previous PV energy requirement values.

The share of energy consumed in the processing of each material is summarized in Table 13 and represented graphically in Fig. 2. It allows for the identification of the most energetically intensive materials processes. It has to be emphasized that the energy involved in processing the ITO represents about 87% of the total. This is a bottleneck in the fabrication of organic solar modules and intensive research is carried out to find an alternative transparent conducting oxide or polymeric layer to be used as transparent electrode. No clear alternative has been pointed out so far.

3.1.4. Direct energy process

Embodied energy during the direct energy process involves the energy consumption in the different steps during the processing

Table 12Material inventory for R2R processing of 3050 cm² (functional unit) and 1 m² organic PV modules processed surface.

	Unit	3050 cm ² Module	1 m ² Processed surface (67% active area)
S1 ITO electrode processing			
PET/ITO substrate	cm ²	3050.00	10,000.00
PET film	cm ³	39.65	130.00
UV curable etch resist substance	g	1	3.28
CuCl ₂	g	0.08	0.25
Water	L	0.10	0.52
NaOH	g	0.31	1.66
Demineralised water	L	0.04	0.21
S2 ET coating			
Zn(OAc) ₂	g	1.38	0.40
KOH	g	0.69	0.20
MeOH	L	0.01	1.66
Acetone	mL	1.01	3.32
Isopropanol	g	7.86	25.77
MEA	g	0.01	0.04
S3 active layer deposition			
P3HT	g	0.03	0.10
PCBM	g	0.02	0.08
chlorobenzene	mL	2	6.56
S4 PEDOT:PSS deposition			
Isopropanol	g	12.36	40.52
PEDOT:PSS	g	9	29.51
S5 electrode deposition			
Silver ink (PV 410)	g	6	19.67
S6 encapsulation			
3 M 467 MPF	g	15.43	50.6
PET (2side)	g	22.19	72.75

of the module, from input materials to the final PV module, as shown in Table 14. All the considered energy inputs are electrical; therefore, the total embedded energy in Table 15 is expressed in electrical Wh, giving 7.48 kWh.

In order to compare with other LCA studies, it is convenient to know the value in Equivalent Primary Energy (EPE), here being 76.99 MJ—assuming a 35% of efficiency of an EPE to electrical energy.

Regarding the energy directly consumed in the manufacturing processes, PEDOT:PSS deposition is the more consuming step, accounting for more than one third of the total energy consumption during the manufacture (35.31%), followed from a short distance by both electrodes processing: silver deposition and ITO patterning (27.89% and 23.23%, respectively). The electron

¹ For the conversion efficiency for electricity production, we used a value of 0.35. For the conversion efficiency of thermal energy consumption to primary energy equivalent, we used a value of 0.8.

transport layer deposition accounts for almost 10% of the total energy, and active layer is one of the less energy intensive processes (5.38%), as shown in Fig. 3.

Important reductions of direct process energy in an OSC fabrication have been achieved, as expected for a newly developed PV technology, the direct process energy accounts for about one quarter of the embedded energy in materials, 76.99–302.27 MJ, as it is shown graphically in Fig. 4.

3.1.5. Energy pay-back time and GHG avoided emissions

Energy pay-back time (EPBT) is the time required for the solar PV system to generate the equivalent amount of energy consumed in the construction and decommissioning phases. The energy payback time as an indicator of energy performance has an appeal because of their similarity with economic payback times. The EPBT is additive, it means that EPBT values for the PV system components can simply be added up to obtain the total PV system EPBT. However, a drawback of EPBT is that it does not account for the energy gain during the rest of the economic lifetime. Then, we

Table 13

Embodied energy for input materials in MJ (EPE) for 1 m² processed surface of organic PV modules produced by R2R processing, ProcessOne (active area 67%).

	<i>EPE per 1 m² processed surface (67% active area)</i>
PET film	14.38
ITO on PET substrate	253.31
UV curable etch resist substance	0.66
CuCl ₂	0.02
NaOH	0.04
Demineralised water	6.39E-07
Zn(OAc) ₂	0.0131
KOH	0.25
MeOH	4.79E-02
Acetone	0.17
MEA	0.15
P3HT	0.18
PCBM	0.87
Chlorobenzene	0.51
Isopropanol	2.42
PEDOT:PSS	4.70
Silver ink (PV 410)	4.13
3 M 467 MPF	4.09
PET (2fm same area FU)	5.87
SUBTOTAL	302.27

use an indicator that combines EPBT with economic lifetime, fulfilling this requirement: the Energy Return Factor (ERF) which expresses the total amount of energy saved per unit invested energy. But a disadvantage of the ERF indicator is that it is not additive, i.e. ERF values of different system components cannot be added to obtain the ERF of the total system.

First, we calculate the energy embedded in the production process of all the materials identified in the inventory, and then we add the energy process of the organic solar cell fabrication and the module fabrication. The output of the calculation is the energy embedded per surface of the PV module. Tables 13 and 14 show an embodied energy of 379.26 MJ (EPE) required to process 1 m² surface (67% of active area) of organic PV modules by R2R processing (ProcessOne).

In order to calculate the energy produced by the PV system during its operative lifetime, some assumptions have to be made: first, the efficiency of the produced organic PV modules is varied from 1.25% to 3% (efficiencies already obtained for laboratory cells), 5% and 10% (forecast for module efficiency on industrial level in 2020); second, the isolation level used for the calculation of the energy produced by the PV system during its operation is set to 1700 kWh per square meter, typical of European southern countries and representative of a world average, and finally, we consider a 15 years life-time for the system, which is low compared with other PV technologies (usually 20–30 years), but realistic in terms of the aims for 2013 of the European Photovoltaic Technology Platform for organic photovoltaics. The forecasted costs for these figures are $\sim 0.5\text{--}0.6\text{ €/W}_p$ by 2013–2020 and $<0.5\text{ €/W}_p$ after 2020 [36]. In order to obtain significant figures that allow us to obtain a global view of the environmental assessment of the organic photovoltaic technology, these parameters will be compared with the published values for other well known photovoltaic technologies.

Also, we performed the Energy Pay-Back Time (EPBT) for an organic PV module as the ratio of calculated embodied energy to annual generated energy by the module, and the Energy Return Factor (ERF) as the ratio of lifetime to energy pay-back time ERF. The generated energy is very much dependent on the final system performance. We assume a realistic performance ratio of 0.8. The calculation for the saved EPE, EPBT and ERF is presented in Table 15.

Photovoltaic systems do not generate green house gas (GHG) emissions during its electricity production stage, but if we consider the entire life cycle, then the pollutant emissions during

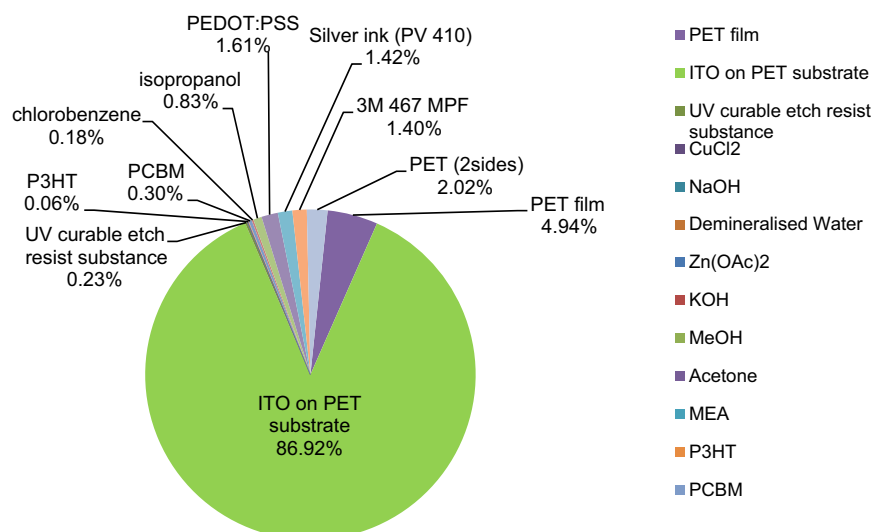


Fig. 2. Calculated share of the embodied energy in the considered input materials to the direct production, for the organic solar module.

Table 14

Energy consumptions during R2R processing (ProcessOne) of an organic (P3HT:PCBM) PV modules.

	Electrical energy consumption (Wh el)	
	3050 cm ² Processed surface	1 m ² Processed surface (67% active area)
S1 ITO electrode processing		
UV curable etch resist screen printing	303.03	993.54
Curing	75.76	248.39
Etching	151.52	496.77
S2 ET coating		
ZnO ink preparation	51.80	169.82
ZnO coating SD	33.33	109.29
Layer drying	100.00	327.87
S3 active layer deposition		
P3HT ink preparation	2	6.56
P3HT:PCBM coating SD	20.83	68.31
Layer drying	100.00	327.87
S4 PEDOT:PSS deposition		
PEDOT:PSS ink preparation	0.45	1.48
PEDOT:PSS slot-die coating	138.89	455.37
Drying	666.67	2185.79
S5 electrode deposition		
Silver electrode screen-printing	636.67	2087.43
S6 lamination		
Encapsulation by R2R lamination	2.04	6.68
Subtotal (W _{el})	2282.97	7485.16
Subtotal (MJ EPE)	23.48	76.99

Table 15

EPBT and ERF for 1 m² processed surface of organic PV modules prepared by R2R processing for different efficiencies and percentages of active area.

Active area (%)	Efficiency (%)	EPE (MJ/year)	EPBT	ERF
50.00	1.25	87.43	4.34	3.46
	2.00	139.89	2.71	5.53
	2.30	160.87	2.36	6.36
	3.00	209.83	1.81	8.30
	5.00	349.71	1.08	13.83
	10.00	699.43	0.54	27.66
67.00	1.25	117.15	3.24	4.63
	2.00	187.45	2.02	7.41
	2.30	215.56	1.76	8.53
	3.00	281.17	1.35	11.12
	5.00	468.62	0.81	18.53
	10.00	937.23	0.40	37.07
85.00	1.25	148.63	2.55	5.88
	2.00	237.81	1.59	9.41
	2.30	273.48	1.39	10.82
	3.00	356.71	1.06	14.11
	5.00	594.51	0.64	23.51
	10.00	1189.03	0.32	47.03

the fabrication, transport, decommissioning and recycling stages should be taken into account. The method used here is that the emissions are calculated using as starting point of the embedded energy, which is one of the outputs of the previous energy pay-back time calculation. Then we assume a determined energy mix for the location of the facility, where the modules are produced. As indicated previously, for ProcessOne we have used the energy mix for Denmark (425.88 g-eq-CO₂/KW_{el} in 2008,

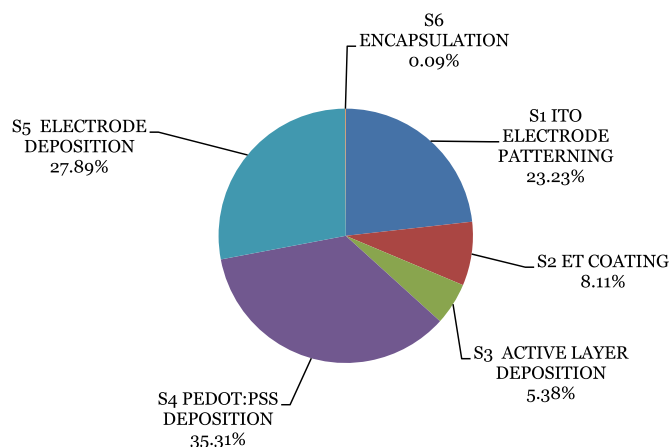
DIRECT PROCESS ENERGY

Fig. 3. Calculated distribution of the energy consumption in the 'production steps' (direct process energy), for the organic solar module.

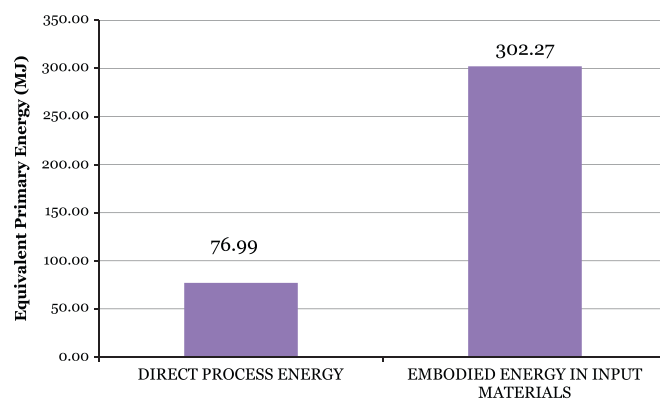


Fig. 4. Embedded Energy in 1 m² processed surface of organic solar modules (with an active area of 67%). The energy is given in Equivalent Primary Energy (EPE MJ).

Table 16

CO₂ emission factor of organic photovoltaic modules. Two values of nominal efficiency are considered, the 1 m² processed surface of modules has 67% of an active area with its fabrication assumed to be in Denmark and its utilization is assumed in the Mediterranean situation (1700 kWh/m²/year of an average irradiance).

Module efficiency (%)	Embodied CO ₂ (kg eq-CO ₂)	E _{gen} during module life-time (kWh _{el})	CO ₂ emission factor (g eq-CO ₂ /kWh _{el})
2	15.49	273.36	56.65
3	15.49	410.04	37.77

A life-time of 15 years and a performance ratio of 0.8 are assumed.

[37]). This allows us to calculate the CO₂ emissions per square meter of module during the life-time of the system, also called the embodied CO₂, which are presented in Table 16.

3.2. Previously reported LCA studies

For polymeric solar cells, two studies have been published very recently; the first one presents an EPBT calculation for laboratory solar cells with 1 cm² of cell area. The active layer is a blend of poly-3-hexylthiophene and PCBM (the same as ProcessOne module); the electrodes are ITO and a bilayer of Ca and Al [19]. For this typical laboratory cell, the EPBT is 4 years for a nominal

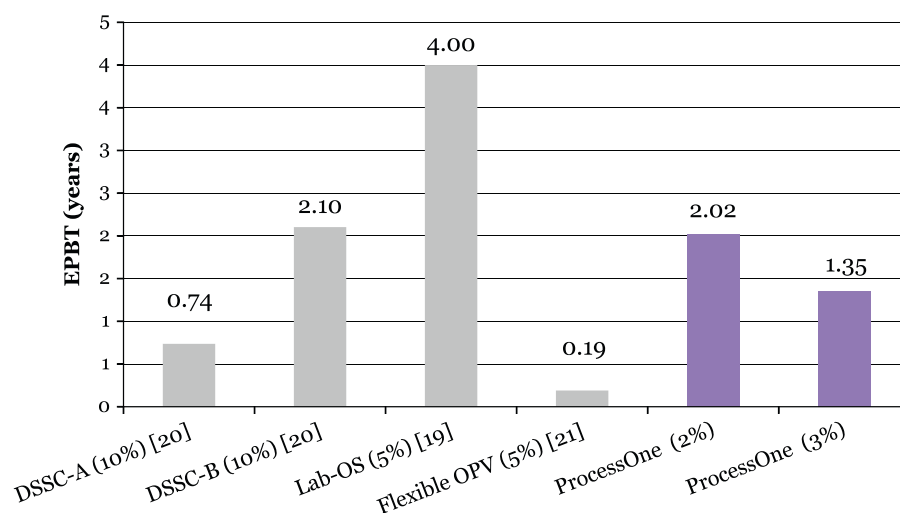


Fig. 5. Energy Payback Time for PV modules technologies. South Mediterranean irradiance ($1700 \text{ kWh/m}^2/\text{year}$) and a performance ratio of 0.8 are assumed. The module efficiency is shown in brackets. DS stand for Dye Sensitized modules, and A and B refer to the low and high values of the energy range.

efficiency of 5% that could be reduced to 2 years in case that 10% efficiency will be achieved. Since laboratory production is far from optimal regarding energy consumption and material usage, these figures can be considered as a cap which already compares well with other much more developed inorganic PV technologies. Roes et al. [21] presented a calculation which takes into account environmental and economical evaluation of polymer photovoltaic modules with glass and PET substrates also on a laboratory scale production; the functional unit for the comparison with other PV technologies is a 25 year lifetime of the system, and therefore they have considered the need for replacement of organic modules, since the lifetime of real modules is still low (around 1 year maximum) which makes the cost calculation more realistic and provides a cost for organic PV modules on glass, which is 20% higher than crystalline Si. Nevertheless they found that on a watt-peak basis, the environmental impacts are lower for polymer PV systems than for crystalline silicon systems. In some cases as low as 10–20% that silicon PV exhibits. Both studies established a first approach to an LCA of organic photovoltaic technologies which has resulted in good expectations for an OPV. In addition, there is still plenty of room for improvement of the manufacturing process.

3.3. LCA outputs for ProcessOne and comparison with other PV technologies

In this article, a detailed Life Cycle Analysis has been performed. We have demonstrated that for a large-scale roll-to-roll compatible manufacturing process, the expectations arisen from previous studies can be fulfilled. The embedded energy per area, considering an active area of 67% of the modules included in 1 m^2 surface is very promising. For efficiencies already achieved of 2% and 3% (1000 Wm^{-2} , AM1.5G, $72 \pm 2^\circ \text{C}$) by ProcessOne, the Energy Pay-Back Time (EPBT) is 2.02 years for modules 2%, and 1.35 years for modules of 3%, as it is shown in Table 15. All of the mentioned efficiencies have been measured in devices [32]. In Fig. 5, we show a comparison between different EBPT of organic technologies, where it can be remarked that modules produced by ProcessOne compares well.

For a full roll-to-roll process where the total area of processed polymer was around 60 m^2 per run [30], the average efficiency was $(1.20 \pm 0.07)\%$, which delivers an EPBT of 3.24 years. However for this process, it is realistic that efficiencies of 2–3% will be

achieved on the short term of an EPBT of 2.02–1.35 years can be expected.

4. Conclusions

A life cycle assessment of the production of organic photovoltaic modules by ProcessOne, a roll-to-toll manufacturing technique, has been performed. The results show that this technology has a low environmental impact in terms of embedded energy, GHG emissions and energy pay-back time. For a typical module of 3% efficiency, and an active area of 67% of module surface, the direct process energy is 76.96 MJ/m^2 and the energy embedded in the materials is 302.27 MJ/m^2 , which delivers an energy pay-back time of 1.35 years. These values have also been calculated for other efficiencies and active area percentage. In all cases, the results compare well with other organic PV technologies.

Also, it is worth to emphasize that a more efficient use of the ITO covered substrates has to be addressed. This will imply a rethinking of the etching process, where 65.2% of the initial amount of an ITO is lost. Avoiding the etching process and substituting it with a directly patterned deposition method for an ITO would be a step forward. In the end, all use of an ITO should be avoided, the share of energy embedded that arises from the use of an ITO as electrode is the highest of all input materials, almost 87%. Also the economical cost of Indium and its scarcity makes this element a bottleneck for a competitive price per watt peak.

Finally, since the embedded energy in the modules (materials and direct process) has been steadily reduced during the past few years for all PV technologies, the relative share of BOS data is increasing when the full PV generator system is considered. In the near future, a more energy efficient process of all components included in the BOS will be mandatory for the final environmental impact of PV systems for electricity production at large scale to be further reduced.

Acknowledgements

This work was supported by the Danish Strategic Research Council (DSF 2104-05-0052 and 2104-07-0022), EUDP (j. nr. 64009-0050), by the Spanish Ministry of Science and Innovation (Consolider-HOPE CSD2007-00007), by Comunidad

Autónoma de la Región de Murcia (CARM-D429-2008) and Antonio Urbina wants to acknowledge financial support from Fundación Séneca de Murcia (exp. 14898/EE10/10).

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