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

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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%.

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 CO_2 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.

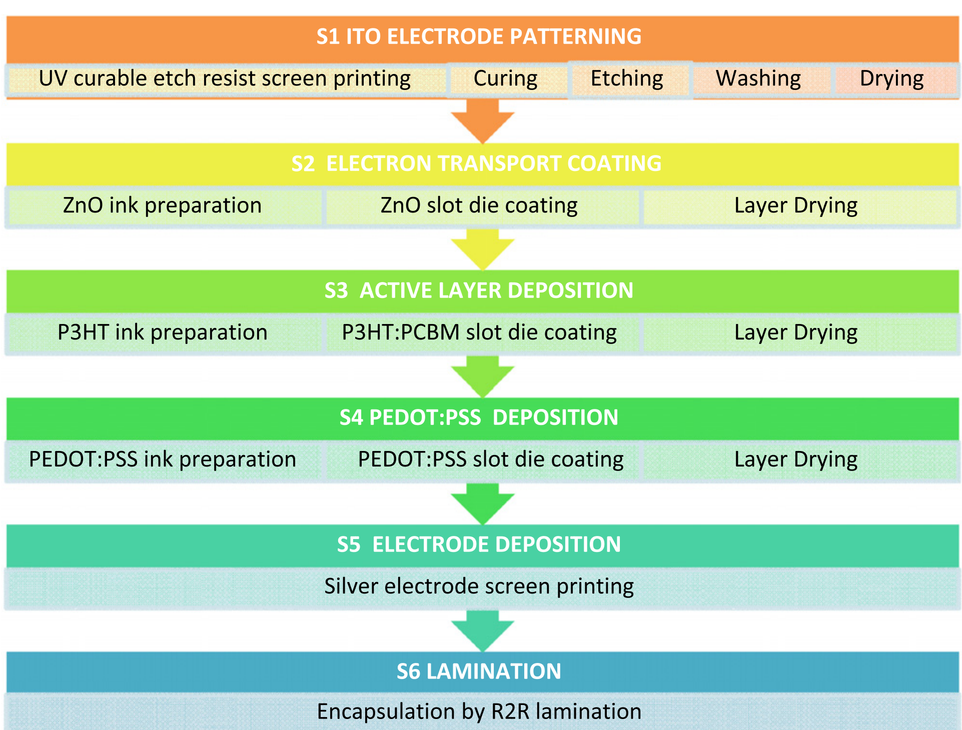

Fig. 1. Steps and substeps during the ProcessOne PV module processing.