REFINED LIFE-CYCLE ASSESSMENT OF POLYMER SOLAR CELLS

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ABSTRACT: A refined life-cycle assessment of polymer solar cells is presented with a focus on critical components, i.e. the transparent conductive ITO layer and the encapsulation components. This present analysis gives a comprehensive sketch of the full environmental potential of polymer-OPV in comparison with other PV technologies. It is shown that on a m^2 basis the environmental characteristics of polymer-OPV are highly beneficial, while on a watt-peak and on a kWh basis, these benefits are – at the current level of the development - still (over-)compensated by low module efficiency and limited lifetime expectancy. The findings of this study underscore that, from an environmental and sustainability point of view, the replacement of the ITO layer and the optimization of encapsulation concepts should be in the spotlight of any near-term R&D efforts of the OPV community. Solutions to both of these technological issues are actively pursued. Some of these are discussed as examples in this paper.

Keywords: Life-cycle assessment, polymer solar cells, OPV

1 INTRODUCTION

Polymer based photovoltaics are in a development stage of continuous progress in recent years. Increasing record efficiencies and improved operational lifetimes are published on a regular basis, reaching by now values of > 8% and thousands of hours for record devices [1, 2]. Moreover, the demonstrated manufacturability with fast roll-based solution deposition techniques and the minute amounts of material required for the light absorbing photoactive layer continue to suggest that this technology may lead to viable commercial applications. Early promotional prototype products (solar bags and backpacks) are indeed being brought to the market in the last few years, primarily by the US based manufacturer Konarka.

In the context of the described development, the environmental profiling of polymer-OPV by life-cycle assessment is of increasing interest. This type of studies can be used in different ways, i.e., in a comparative way for the identification of environmental advantages or disadvantages compared with other PV technologies and/or in a way which helps to identify the most urgent R&D needs (from an environmental point of view). Excellent first LCA studies of polymer-OPV have already been published in the last two years [3, 4, 5]. This study adds to those by a critical reassessment and differentiation of the most relevant environmental components, i.e., the ITO layer and the encapsulation scheme. This leads to a comprehensive overall picture of the environmental profile of the current state-of-the-art of polymer-OPV technology.

2 SCOPE, WORKING TOOLS & DEFINITIONS

2.1 Scope

The scope of the LCA is primarily focused on the production phase of the life-cycle of a polymer OPV module (including raw materials extraction). This is justified by the fact that practically all environmental loads are generated in this phase [6].

The main attention of this LCA study is primarily directed on an embedded energy analysis of the PV modules. The embedded energy arises, almost entirely, from materials and processing energies used during the module production and all commonly cited environmental quality indicators, like energy payback times (EPT), energy return factors (ERF) and greenhouse gas emissions (GHG) can be directly derived from it.

The use phase of the life-cycle is addressed by means of indicative assumptions envisioning future applications in grid-connected, power-generating roof-top systems. Other applications during the use phase, e.g. in mobile electronics devices are not explicitly addressed here despite the fact that most OPV roadmaps expect such applications to be the first commercial products .

The end-of-life phase (disposal or recycling) is not included due to insufficient information at the current early stage of the development.

All values are expressed in units of 1 m^2 of a polymer- OPV module, assuming production processes as used in an existing roll-based pilot line facility at Risø/Denmark (with an annual production capacity of ~50 kW_p). In LCA terminology this is the "functional unit" of this study.

Relevant resource limitation issues, i.e., regarding indium and silver, are discussed based on latest insights from the relevant literature

2.2 Working tools and input data sources

The commercial and widely used software Simapro (version 7.3) has been used in conjunction with its integrated Ecoinvent 2.0 database. The calculation of the different environmental quality indicators has been carried out on the basis of the following predefined methods within Simapro and by following the ISO 14040 standard:

- CED V.1.04 (for embedded energy).
- IPCC 2007 GWP100 (for greenhouse gas emissions).

The input data sources include Risø (for the embedded energies of the processing steps in the

described 50 kW$_p$ pilot line facility and parts of the materials) as well as the Ecoinvent database (2.0) and various publications for embedded energies of another part of the materials. A particular focus was put on the embedded energy of sputter-coated ITO layers on PET foils by collecting processing information from the HOLST Centre (Netherlands) and Umicore (Belgium), where such layers are produced in industrially relevant settings.

2.3 Definitions

a - Embedded energy (EE)
 = Total energy consumed for the production of polymer OPV-modules (material and processes).
It is expressed in MJ primary energy equivalents, PEE. Factors of 0.37 and 0.8 were used for the conversion of electricity respectively heat into primary energy equivalents (based on the Danish energy mix).

b - Energy payback time (EPT)
= Embedded energy / annual energy output.
The assumptions here are:
- 1 kWh of annual electricity output of a solar module avoids the generation of 1 kWh conventional electricity and is therefore equivalent to 11.4 MJ primary energy (which is an averaged primary energy value required for the production of 1 kWh conventional electricity).
- Performance ratio = 0.75

c - Energy return factor (ERF)
= Energy produced over the entire module lifetime / embedded energy.

d - Greenhouse gas emissions (GHG)
= All climate relevant emissions during the life cycle expressed as CO_2-equivalents.
The values can be derived from the embedded energy by multiplication with an emission factor (46.5g CO_2-eq/MJ = 530g CO_2-eq/kWh for an average EU electricity mix).
For expressing climate relevant emissions other than CO_2 as "CO_2 equivalents" weighting factors relative to CO_2 are applied [7], e.g., $N_2O = 298$, $SF_6 = 22.800$.

3   RESULTS AND DISCUSSION

All results in this section are based on the device layout as developed and processed by Risø at their roll-based manufacturing facility [8]. These devices are characterized, among others, by an active area of 68% and a general structure as shown in figure 1.
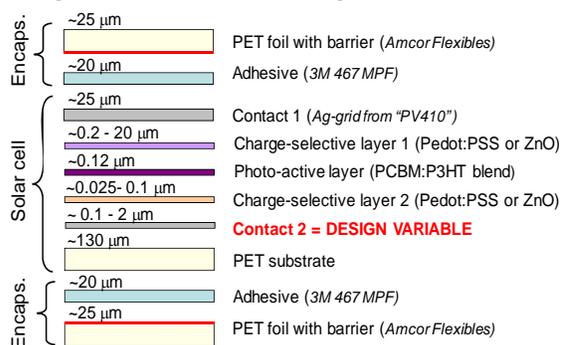
Figure 1: General device structure of polymer-OPV modules as processed by Risø.

A generalized processing sequence can be described with the steps shown in the scheme below (figure 2). The corresponding processing techniques are indicated in brackets. Step 1^+ in this sequence, i.e. patterning of contact 2 by means of a wet-chemical etching process, is only applicable if contact 2 consists of a sputtered ITO layer.

- Step 1 : Deposition of contact 2 on PET substrate
        (Sputtering or screen-printing/curing)
- Step 1^+: Patterning of contact 2
         (Multiple-step wet-chemical etching process)
- Step 2 : Deposition of charge-selective layer 2
        (Ink preparation, slot-dye coating, drying)
- Step 3 : Deposition of photoactive P3HT/PCBM layer
        (Ink preparation, slot-dye coating, drying)
- Step 4 : Deposition of charge-selective layer 1
        (Ink preparation, slot-dye coating, drying)
- Step 5 : Deposition of contact 1
        (Screen-printing/curing)
- Step 6 : Encapsulation
        (Roll-based lamination).

Figure 2: Generalized sequence of processing steps for the manufacturing of polymer-OPV modules.

In the following the focus is first on "contact 2" of figure 1, which is a transparent ITO layer of ~ 90 nm thickness in the benchmark design (see section 3.1). In two variations from this benchmark design, "contact 2" is realized with other materials than ITO and the consequences of this replacement on the embedded energy are analyzed (see 3.2 and 3.3). In section 3.4 variations of the encapsulation components are addressed. The implications of the embedded energy analysis of sections 3.1-3.4 for commonly cited environmental quality indicators of PV modules, i.e. EPT, ERF and GHG, are elaborated in section 3.5, which also contains a comparison with other PV technologies. Finally, section 3.6 provides a discussion of indium and silver in terms of materials scarcity.

3.1 Benchmark configuration (contact 2 = ITO)
In the benchmark configuration, "contact 2" of the generalized structure in figure 1 consists of a 90 nm thick ITO layer deposited by magnetron sputtering. Moreover, the "charge selective layers 1 and 2" are a 20 μm thick Pedot:PSS layer and a 0.25 μm thick ZnO layer, respectively.
The life-cycle assessment of this benchmark system follows essentially the analysis published in [5], with the exception of the sputtered ITO layer. This latter component was assumed to require > 10 kWh/m^2 power consumption for the sputtering process in [5]. The data inventory in this present study suggests that significantly lower values of ~ 0.5-1.5 kWh/m^2 (~5-15 MJ/m^2), can be achieved with the most efficient, high-throughput sputter tools, currently available. The existence of largely varying power consumption values per coated area for different ITO sputter tools is also apparent from a recent equipment survey in Photon International [9].
Including further contributions from the ITO sputtering target and sputtering gas (Ar), we estimate total embedded energy values of ~ 20 MJ/m^2 for the sputtered ITO layers, expressed in primary energy equivalents. An experimental validation of this estimation has not been carried out in the frame of this study but will be the subject of future work. It should also be noted, that

this estimation represents the very low end of the range of possible values for sputtered ITO layers and can be significantly higher for less power-efficient sputter tools (up to several multiple times the above stated value of 20 MJ/m^2).

With the above assumptions, the embedded energy breakdown shown in table I results. A total embedded energy of about 130 MJ/m^2 is obtained for this benchmark system from our analysis. Compared with averaged values for other current thin-film PV technologies this value is lower by a factor of approximately 10 ($\sim$ 130 versus $\sim$ 1000-1500 MJ/m^2). It should be noted however, that the "average" thin-film PV technology is produced as glass based laminates and that this laminated encapsulation structure alone brings along embodied energy values of several hundreds of MJ/m^2 (see section 3.4). From this point of view the comparability of an "average" thin-film PV module and the benchmark polymer-OPV module described here is limited since the encapsulation scheme of the latter only adds up to $\sim$ 10 MJ/m^2 and is most certainly not appropriate for power generation devices in outdoor conditions.

Table I: Embedded energy breakdown of the ITO benchmark system

	Materials (MJ/m^2)	Processing (MJ/m^2)	Σ Materials &processing (MJ/m^2)
Step 1 & 1$^+$	~15	~ 35	~50
Step 2	< 1	~ 5	~6
Step 3	~2	~4	~6
Step 4	~7	~27	~34
Step 5	~4	~ 20	~24
Step 6	~10	<1	~10
Totals	**~38**	**~92**	**~ 130**

3.2 1st alternative configuration (contact 2 = Al/Cr)

An alternative electrode configuration uses a sputter-deposited Al (100 nm)/Cr (15 nm) layer as "contact 2". A "charge selective contact 2" is not required in this concept, which is why step 2 is absent from the processing sequence shown in figure 2. Here, we refer to this as "ISE concept", since this electrode configuration was first introduced by the Fraunhofer Institute ISE.

Since all the following steps remain unchanged, the following embedded energy breakdown for this alternative electrode concept can readily be derived (see table II).

Table II: Embedded energy breakdown of 1st alternative electrode configuration (= ISE concept).

	Materials (MJ/m^2)	Processing (MJ/m^2)	Σ Materials &processing (MJ /m^2)
Step 1	~15	~20	~35
Step 2	-	-	-
Step 3	~2	~4	~6
Step 4	~7	~27	~34
Step 5	~4	~ 20	~24
Step 6	~10	<1	~10
Totals	**~38**	**~71**	**~ 109**

3.3 2nd alternative configuration (contact 2 = Ag-grid)

Another alternative electrode configuration uses a screen-printed Ag-grid electrode of 2 μm thickness – buried in the substrate - in combination with a 100 nm thick layer of the highly conducting "Orgacon TM"-Pedot:PSS (Agfa Gevaert) for the charge collection in contact 2. In this case the polarity of the electrode configuration is inverted with respect to the two other systems discussed in section 3.1 and 3.2 and consequently the "charge selective layer 1" consists of a 0.25 μm ZnO layer in this case. All other processing steps are again assumed identical here which results in the values shown in table III. Here, we refer to this electrode configuration as "HOLST concept", since it was first introduced by the HOLST Centre. It should be noted that energy contributions for the burying of the Ag-grid have not been accounted for in our assessment due to a corresponding data gap in the process inventory.

Table III: Embedded energy breakdown of 2nd alternative electrode configuration (= HOLST concept).

	Materials (MJ/m^2)	Processing (MJ/m^2)	Σ Materials &processing (MJ/m^2)
Step 1	~15	~20	~35
Step 2	< 1	~5	~6
Step 3	~2	~4	~6
Step 4	< 1	~5	~6
Step 5	~4	~ 20	~24
Step 6	~10	<1	~10
Totals	**~32**	**~55**	**~ 87**

Tables I – III suggest that the discussed alternative electrode configurations may result in advantageous embedded energy values compared with the ITO benchmark system. However, when taking into account the uncertainty considerations here below, it becomes clear that such a conclusion would be premature and it is more appropriate to indicate an approximate range of 80 – 150 MJ/m^2 for all three configurations. These considerations are as follows:

1. Generally, all PV module configurations discussed in this paper are pre-commercial systems, manufactured on a lab-scale pilot line. Significant uncertainties compared with production facilities in industrial settings therefore exist.
2. A patterning step (step 1$^+$) has only been assigned to the benchmark configuration in the above assessments, but not for the two alternative electrode configurations. This may be inappropriate and the removal of this step would reduce the value of the benchmark system by ~15 MJ/m^2 (alternatively the addition of this step would add 15 MJ/m^2 to the two other configurations).
3. The above mentioned data gap in the process inventory of the 2nd alternative electrode configuration (relating to the "burying"of the Ag-grid electrode) implies a probable underestimation of the embedded energy value calculated for this system in table III.

3.4 Variations in the encapsulation components

The encapsulation scheme envisioned in the benchmark system of this study (as described in section 3.1) is based on a "cold lamination" procedure

using adhesives and thin PET foils with basic moisture barrier coatings. While such an encapsulation structure may be sufficient for relatively short-lived mobile electronics applications, power generation applications are expected to require substantially different encapsulation schemes providing a more stringent and robust protection from humidity and oxygen ingress as well as mechanical impacts.

Since the large majority of current thin-film PV modules are manufactured as glass-glass laminates with EVA encapsulants, this structure (glass/EVA/glass) is considered here as a benchmark encapsulation scheme. However, this consideration is not supposed to suggest that this is indeed a probable encapsulation structure for viable power generating OPV products in the future. As yet, such products do not exist and thus the corresponding encapsulation structures and methods are also unknown to date.

Another "imaginary" encapsulation scheme considered here is the structure steel-foil/EVA/ETFE, in analogy to flexible PV modules manufactured on metal substrates. Such a structure would probably still need to integrate additional components in order to comply with all requirements for outdoor use, but can serve as an indicative benchmark here.

More specifically, the thicknesses of the materials envisioned for the two "imaginary" encapsulation concepts described above are:

glass pane: 2.3 mm, EVA foil: 500 μm, stainless steel foil: 100 μm, ETFE foil: 100 μm

Regarding the processing, the lamination with EVA is carried out in vacuum laminators at elevated temperatures of 140-150 °C for up to ~ 30 min.

The embedded energy values of all three encapsulation schemes described here are shown in table IV, where the "cold processing" of the benchmark laminate is referred to as "Encaps. Variant 0", while the processing of the glass/EVA/glass and steel-foil/EVA/ETFE laminates are referred to as "Encaps. Variant 1" and "Encaps. Variant 2".

Table IV: Embedded energy breakdown of alternative encapsulation components (and processes)

	Materials	Processing	Σ Materials &processing
	(MJ/m^2)	(MJ/m^2)	(MJ/m^2)
"Encaps. Variant 0"	~10	< 1	~10
"Encaps. Variant 1"	~300	~80	~380
"Encaps. Variant 2"	~120	~80	~200

It is clear from table IV that for power generating devices an encapsulation scheme similar to state-of-the-art rigid or flexible PV modules would amount to an additional contributions to the embedded energy of ~200-400 MJ/m^2 (Encaps. Variants 1 and 2) and thus become the dominant factor (by far) of the total embodied energy of the polymer-OPV module (of then ~300-500 MJ/m^2).

3.5 Implications for EPT, GHG and ERF

From the embedded energy assessments of the previous sections, EPT, GHG for a polymer-OPV module of 4% efficiency can be readily derived based on the GHG emission factor given in section 2.2 (46.5 g CO$_2$-eq/MJ) and based on an annual electricity generation of ~50 kWh/m^2 (for a Southern European location with an

illumination level of 1700 kWh/m^2/y and a performance ratio of 0.75).

The above assumptions lead to the values here below:

- EPT ~ 0.5 – 0.8 years,

- GHG ~ 14-23 kg CO$_2$-eq./m^2 (~350-580g CO$_2$-eq/W$_p$).

Even at this early development stage, these values compare favorably with other thin film PV technologies, for which EPT and GHG values on the module level are in a range of ~0.5-1.5 years and 35-80 kg CO2-eq/m^2 (~350-800g CO$_2$-eq./W$_p$) [6].

However, the most meaningful way to express the environmental profile for power-generating PV modules is in units of kWh produced by those modules throughout their entire service-life. An environmental quality indicator based on this unit is the ERF (see section 2.3); likewise the GHG can be expressed in this unit (kWh) as well..

Assuming, for example, a service lifetime of 10 years and an average annual degradation rate of 3% for polymer OPV modules results in an ERF ~ 10-16, and a GHG of 32-54 g CO$_2$-eq/kWh.

Since other thin film PV technologies are at a more advanced development stage, they have a higher service lifetime expectancy as well as a lower annual degradation rate: we assume here a service life of 30 y and a degradation rate of 1% p.a. This leads to ERF values of ~25-60 and GHG of ~10-24 g CO$_2$-eq/kWh. We therefore conclude that at the current early development stage, the environmental profile of polymer-OPV on a kWh basis is not yet competitive with other thin-film PV technologies. As indicated above this is due to the lower module efficiency and lower lifetime expectancy.

3.6 Discussion of indium and silver scarcity issues

This section addresses issues of (future) resource scarcity for indium and silver since the transparent electrode concepts discussed in this paper make use of either of those two metals. Both are critically discussed in this context since many years and relevant information is summarized regularly. The most recent update can be found in a 2011 EC report entitled "Critical raw materials for the EU" [10] By sketching the demand and supply of commodity metals now and in the future, probable supply bottlenecks are identified in this report. The corresponding information is summarized in table V. The (resource scarcity) indicators shown in the table point to potential future supply problems. The larger the indicator (= demand/primary production 2006), the larger the probability of future supply bottlenecks and sharply rising price levels.

Table V: Current and future demand and supply information for indium and silver and critical resource indicators (see text).

Raw material	Production 2006 (t)	Demand from emerging technologies 2006 (t)	Demand from emerging technologies 2030 (t)	Indicator 2006	Indicator 2030
Indium	581	234	1911	0.40	3.29
Silver	19,051	5,342	15,823	0.28	0.83

Clearly, the supply/demand balance of indium appears to be extremely stressed. The situation for silver – while somewhat less extreme – does not look much better.

Major price volatilities will certainly continue to be seen for both of these elements in the future and technological developments in the area of polymer-OPV (as well as PV in general) should therefore better avoid their use if possible.

4 CONCLUSIONS

This paper provides a comprehensive picture of the environmental profile of polymer-OPV technology based on a full-scope embedded energy analysis. It is found that for power-generating applications, the embedded energy on the module level is on the order of ~300-500 MJ/m^2, resulting to a large extent from the encapsulation scheme with a contribution of ~200-400 MJ/m^2.

Thanks to these very low embedded energy values, it is shown that the environmental profile of polymer-OPV is highly competitive with other thin-film PV technologies on a m^2 basis as demonstrated by an EPT < 1 year for example .

However, when expressed in a W_p basis or in the ultimately most relevant kWh basis, this competitiveness is (partially) lost due to the lower module efficiency and lifetime expectancy. For polymer-OPV to become an environmentally viable power-generating PV technology these latter two parameters (module efficiency and lifetime) necessarily need to be further improved.

Regarding the transparent ITO electrode, the replacement of this compound by alternative electrode materials - which are not based on indium - is desirable, primarily from the point of view of indium scarcity. Such alternatives should ideally not be based on silver though, which is expected to face its own critical supply/demand

imbalances in the near and longer term future as well.

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6 ACKNOWLEDGMENTS