WP 5.4.:
Sustainability analysis of nanotechnology

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1. Introduction and scope

Work package (WP) 5.4 deals with a **sustainability analysis of nanotechnology** used for the development of organic semiconductors. The focus of this report is on the **atmospherical environmental impact (climate change) and energy use** resulting from the development of **organic photovoltaics** (OPV). Organic solar cells are nano-enabled photovoltaic cells which contain at least one organic semiconducting molecule within the photoactive layer [1, 2]. Light will specifically be shed on the **all-organic solid-state** solar cells, *i.e.* **polymer and molecular OPV**. Their potential economic and social impact has already been discussed in WPs 5.2 and 5.3, respectively. Other organic electronic technologies, such as organic light-emitting diodes (OLEDs) or organic field-effect transistors (OFETs), are not considered. Furthermore, we explicitly focus on the **material acquisition and manufacturing stages** of the OPV life cycle. Intact solar cells are not considered to be problematic during their use phase. Figure 1 displays the notion of a product's life cycle stages.

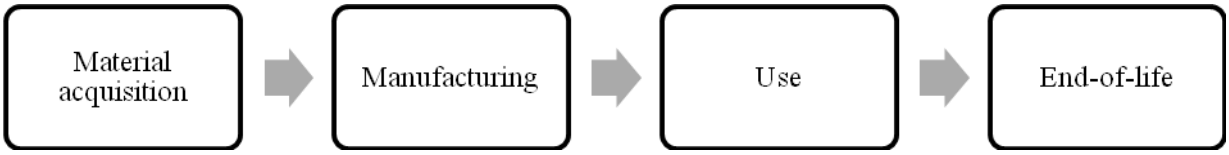

Figure 1: Product life cycle stages

Solar energy systems should provide significant environmental benefits in comparison to conventional energy sources, thus contributing to the sustainable development of human activities [3]. However, the wide scale deployment of OPV may imply unforeseen negative environmental impacts if not properly assessed over their full life cycle [4]. This report aims at partially alleviating this concern. To this extent, a **literature study** is performed and **conclusions** regarding OPV sustainability are presented.

2. Literature review

2.1. Available methodologies

To sketch the available methodologies for sustainability assessment we build on the framework as provided by Ness *et al*. (2007) [5]. A similar effort was presented more recently by Gasparatos and Scolobig (2012) [6]. Ness *et al.* divide methodologies into three categories, being (1) indices, (2) product-related assessment methods, and (3) integrated assessment methods based on (a) temporal characteristics, (b) coverage area, and (c) the degree to which it fuses social, environmental and economic aspects. To achieve our goal, as introduced above, **product-related assessment methodologies** are highly suitable as they allow evaluating resource use and environmental impacts through the life cycle of a product. Methods adhering to this branch of methodologies are **life cycle**

analysis (**LCA**), life cycle costing (LCC), product material flow analysis (PMFA), and product energy analysis (PEA). Research may also target integrated assessment methodologies, such as multi-criteria analysis (MCA), cost-benefit analysis (CBA), risk assessment (RA), and impact assessment (IA). Combining several methods from the latter two categories is often referred to as (integrated) technology assessment (TA) [7]. In our case, (extended) LCA studies seem most appropriate.

Health and ecotoxicity effects (which are assessed in risk and impact assessments) will not be covered in detail in this report. In view of its importance, Figure 2 provides an overview of possible exposure routes to man and nature during a nano-enabled product's full life cycle. A recent review by Zimmermann *et al*. (2012) [8] compiles available information about the fate and effect of the components of a general OPV solar cell stack based on the workhorse P3HT and PCBM materials (see Figure 3). It depicts the constitution of a bulk heterojunction (BHJ), making abstraction of the interpenetrating network, organic solar cell having a polymer-fullerene light-absorbing layer (LAL). They conclude that there is a **general lack of information** about fate, behavior as well as potential ecotoxicity of most of the main OPV components and their degradation/transformation products. Exceptions are the ecotoxicity of the oxide interlayer and/or electrode materials (ITO, ZnO, and TiO_2) and fullerenes (PCBM). Based on the available information they find **no evidence for a worrying threat** coming from OPV, but further laboratory fate studies are advisable. Additionally, they warn for improper disposal upon end-of-life when applied on a large scale, a concern already considered for photovoltaic devices by Strange *et al*. (2008) [9].

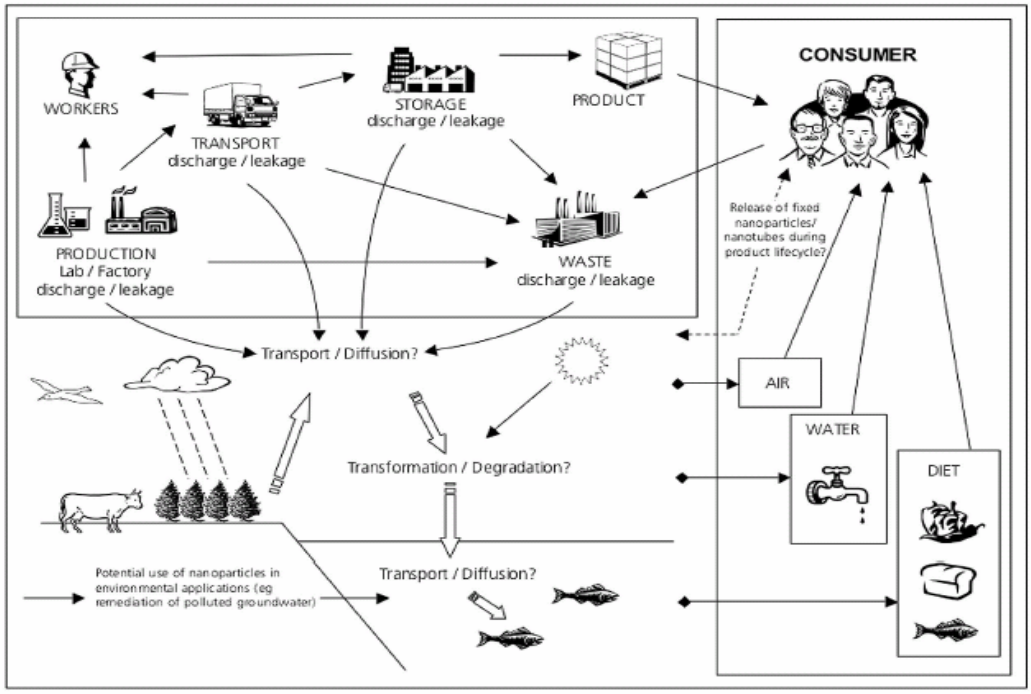

Figure 2: Possible exposure routes for nanomaterials based on current and potential future applications [10]

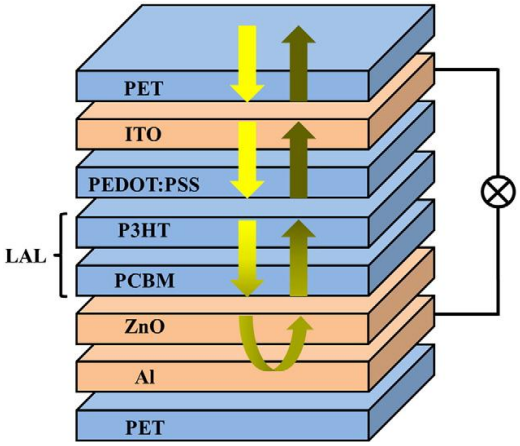

Figure 3: Typical constitution of a bulk heterojunction organic solar cell [8]

2.2. LCA studies

Typically, the steps involved in an LCA are: (1) defining the goals and scope, (2) creating the life cycle inventory (LCI) which quantifies the material and energy inputs, as well as the environmental releases for each unit process, (3) performing a life cycle impact assessment, and (4) interpreting the results [11]. Two types of methods for LCA are distinguished: (1) attributional and (2) consequential LCA. Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems. Consequential LCA is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions [12]. Studies we will report on belong to the first category. Results' interpretation is most meaningful for OPV when comparing its impact to that of other energy resources. The life cycle stages that can be considered are: (1) acquisition of materials, (2) manufacturing, (3) use, (4) transportation, and (5) end-of-life (recycling/disposal). For organic nanomaterials the task of conducting an LCA requires enormous efforts given the **lack of available inventory data** in the commonly used LCA databases, while **little generality** may be gained as processing techniques and manufacturing methods are not yet standardized [4].

Nanomaterials are man-made. Sengül *et al.* (2008) [13] and Kim and Fthenakis (2012) [14] provide a thorough overview of why the manufacturing of nanocomponents is generally **energy-intensive and has low material efficiency**. Some nuance may, nevertheless, be advisory as many decisions have an influence. To this end, Figure 4 represents the key aspects that determine the potential impact of nanocomponents. **Material selection** determines the full life cycle impact of a given component in three main ways: (1) the material's physico-chemical properties influence its toxicological impact, (2) extraction of raw material may require large amounts of energy, deplete natural resources, generate waste(s) that have to be treated, and result in significant land use, and (3) the material determines

which synthesis or manufacturing techniques are suitable. **Manufacturing techniques** can be divided into two groups, being bottom-up and top-down methods. The former create nanoscale dimensions from matter at the atomic level, whereas the latter achieve such dimensions by carving or grinding methods using bulk materials. Each technique has its respective impact. Finally, the material form during the **application** or use phase is the most decisive factor for the environmental impact. If the material is immobilized, no harm should occur, unless breakdown of the composite matrix occurs. The same cannot be said if greater mobility is allowed. Not much is known yet about the **recyclability** of nanomaterials, although it is considered the ideal solution to avoid problems such as bio-accumulation [15]. Having provided this general framework, it may help to understand why the energy demand per functional unit of material for **carbon-based nanomaterials** varies between 1 and 900 GJ/kg [14].

So why continue using organic nanomaterials? The results above are situated at the material level, whereas the impact on device level matters more. Most reviewed studies ascertain that at the device level the energy demand and impact on global warming is lower than that of conventional technologies because the organic nanomaterials are used in small amounts and increase the energy-efficient operation of the device [14]. Therefore, a chronological overview of journal-published LCA studies focusing mostly on climate change and energy use from **organic photovoltaic devices** is provided below.

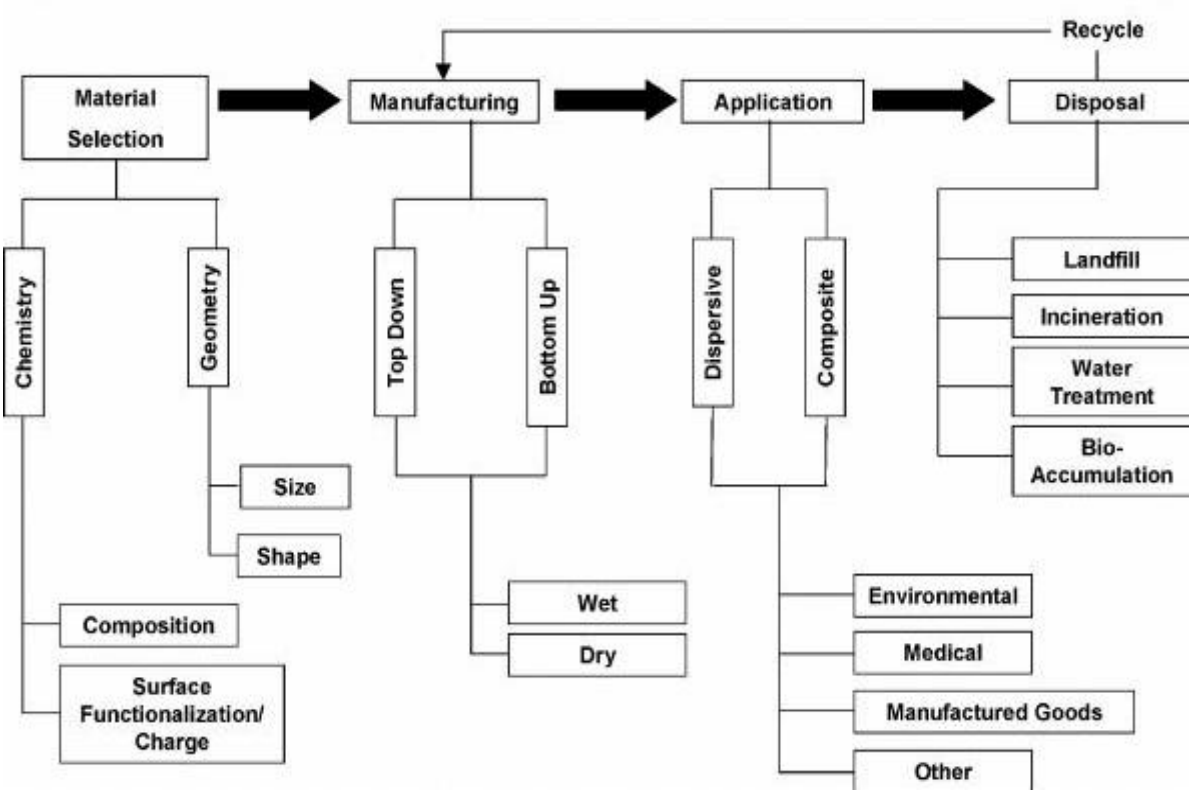

Figure 4: Key aspects that determine the impact of nanocomponents [15]

2.2.1. *Ex-ante* environmental and economic evaluation of polymer photovoltaics

The oldest study available on this topic was performed by **Roes *et al.* (2009)** [11]. They were the first to compile a **LCI and LCC** for polymer photovoltaics (200 cm²/Wp) based on **literature and own estimations**. It considers impacts resulting from **materials acquisition and manufacturing of P3HT/PCBM organic solar cells on glass and PET substrates**. The respective process chains and solar cell build-ups can be found in the appendix (see section 5.1. and 5.2.). From the process chains it can be deduced that the flexible modules are assumed not to be used in grid-connected operation. No balance of system (BOS) is included in their chain, whereas this is the case for the rigid modules on glass. Furthermore, cleaning and annealing are not applied in case of the flexible PV production. The final difference between both processes is that only the **flexible module** was produced on a continuous roll-to-roll (R2R) basis using **gravure printing** for the light absorbing layer (LAL). The **glass-based** module is fabricated using a batch-process using **inkjet printing** for the LAL. The impact of LiF was considered negligible. They found that the **environmental impacts per Wp of output power compared to comparable multicrystalline silicon** (mc-Si) **systems** are **20–60% lower for polymer PV systems with glass** substrates and **80–95% lower for polymer PV systems with PET substrates**. The latter results may, however, be underestimations due to oversimplification of the process chain. However, if one considers a functional unit of 25 years of electricity production it should be noted that if the efficiency of polymer PV cells remains at its current value of about 5%, the **lifetime** of polymer modules **should increase substantially** to realize such environmental benefits. The impacts considered for OPV are non-renewable energy use (NREU), contribution to climate change over 100 years, abiotic depletion, ozone layer depletion, photochemical oxidant formation, acidification, and eutrophication. The most and least environmentally burdensome relative to mc-Si are **acidification** (g SO_2 eq) and **ozone layer depletion** (g CFC-11 eq) for both glass- and PET-based PV systems. Steps contributing most to NREU and climate change are solar glass production, lamination, framing, and BOS for glass-based systems and sputtering and lamination for PET-based systems. The **costs per watt-peak** of polymer PV modules with glass substrates are approximately 20% **higher** compared to mc-Si photovoltaics (4.18 €/Wp *vs.* 3.43€/ Wp). However, taking into account **uncertainties**, this might be an overestimation. If the (cell) efficiency reaches 11%, costs of glass-based polymer PV **could drop to nearly half of the costs** of 2009 mc-Si PV (keeping other things constant). No cost data were available for flexible modules at that time.

2.2.2. Life cycle analysis of organic photovoltaic technologies

A second study by **García-Valverde *et al***. (2010) [16] presents an LCA, targeting energy payback times and CO_2 emission, of the **laboratory production of a typical P3HT/PCBM bulk heterojunction** organic solar cell (1 cm²). Subsequently, from these data the impact of large scale

manufacturing processes for grid-connected **modules** (1 m²) are extrapolated to be compared with those obtained for the **industrial production of other PV technologies**. A representation of the laboratory process used can be found in the appendix (see section 5.3.). Energy and material inputs for the ITO patterning step are disregarded. The representation omits an annealing step at 70 °C in nitrogen atmosphere. Deposition of PEDOT:PSS and the LAL are done by **spin-coating** with a material usage efficiency of only 30%. Energy and nitrogen consumption from the glove box are also taken into account. Their work adds to literature by **estimating the embodied primary energy and raw materials for** 1 kg of regioregular **P3HT** using the Grignard metathesis (GRIM) method, 1 kg of **PCBM** using a method proposed by Hummelen *et al*.(1995) [17], 1 kg of **PEDOT:PSS** following recommendations of Zhan *et al.* (2008) [18], and 1 m² of **ITO-coated glass**. Solvents and reagents were disregarded in the analysis. Nevertheless, most of such chemicals used nowadays are hazardous air pollutants such as volatile organic compounds (e.g. chlorobenzene, toluene, xylene used as solvents) and acids (e.g. hydrochloric acid used in wet processes). Ideally, these should be avoided [19]. Results show that OPV modules **compare favorably with mc-Si**, similarly with thin film and slightly worse than dye sensitized solar cells (DSSC) **regarding the embedded energy** (MJ/m²) using a far from optimum process. The **fabrication of electrodes** is the most energy-costly step. The ITO-electrode is the most energy-costly of both electrodes. Further **increase of efficiency** is needed to decrease the energy payback time (years) and CO_2 emission factor (g CO_2 eq/kWh) if it is to outperform CdTe and DSSC technologies.

2.2.3. Life cycle analysis of polymer solar cell modules prepared using roll-to-roll (R2R) methods under ambient conditions

A third study by **Espinosa *et al*. (2011)** [20] presents an LCA on a **full R2R-coating procedure** used for the manufacturing of **flexible polymer solar cell modules**. The functional unit is 1 m² of processed surface with 67% of active area. The manufacturing process, whose steps and substeps can be found in the appendix (see section 5.4.), is known as **ProcessOne**. All operations except the application of ITO are carried out under **ambient conditions**. The LCA delivered a **material inventory** including solvents and materials that are not present in the final module, and an accountability of the **energy embedded** both in the input materials and in the production processes using the energy mix for Denmark, which is very clean (420.88 g CO_2 eq/kWh). The decommissioning phase has not been taken into account, except for the recycling of some materials (especially solvents). Also BOS was outside the scope. Upon assumption of power conversion efficiencies (PCEs) and lifetime for the modules, calculation and comparison of **energy payback times** (EPBT) is possible. The results showed that an **EPBT** of 2.02 years can be achieved for an organic solar module of 2% efficiency, which can be reduced to **1.35 years** if the **efficiency is 3%**. Consequently, OPV might

outperform CdTe which has the lowest EPBT of all non-organic PV technologies. The study also emphasizes that **replacement of ITO** is necessary both from an energetic as economic point of view.

2.2.4. Life-cycle analysis of product-integrated polymer solar cells

A fourth study by **Espinosa *et al* (2011)** [21] presents an LCA on a product-integrated polymer solar module. The product under revision is a **solar-powered portable lighting system**. The lamp's cross-section can be found in the appendix (see section 5.5.). It sought to provide low-cost reading light and simple rechargeable lighting in developing countries without an electricity grid. The organic solar module used to power the lamp was produced using the **ProcessOne** manufacturing process. The only changes (compared to the previous study) are the size of the modules and the use of different screens for printing the back contacts. The LCA quantifies the **energy use** (9.55 MJ) and **greenhouse gas (GHG) emissions** from **electricity use** during manufacturing. The LCA boundaries **- additionally to previous studies - include transport** and the **end-of-life** (land filling). Transport was found to be contributing most to the greenhouse gas emissions for the OPV module (compared to other building blocks), whereas the manufacturing of OPV raw materials accounts for 77% of GHG emissions in the OPV. The portable lighting system's impact was also compared with other lighting solutions, namely a kerosene lamp, a silicon PV based lamp, a torch with non-rechargeable lead-acid battery and a battery charging station. The analysis reveals that the OPV lamp has a significant advantage, i.e. it has the **lowest embodied energy** of all options. Provided that **challenges** facing this novel technology are efficiently met, the current **EPBT of around 10 years** can be reduced and the device can enter the market of portable lighting devices. Furthermore, it was found to provide **ancillary health benefits over kerosene lighting**, with as little as just 1.5 days for earn-back of the emissions generated during the manufacturing.

2.2.5. Life cycle assessment of ITO-free flexible polymer solar cells prepared by roll-to-roll coating and printing

A fifth study by **Espinosa *et al.* (2012)** [22] presents an LCA, targeting **energy efficiency and GHG emissions**, of a new process that is fully R2R compatible, named **Hiflex**. The manufacturing process steps and materials inventory are given in the appendix (see section 5.6.). It allows for the manufacture of **flexible OPV modules** where the ITO electrode has been replaced in an **inverted device** architecture with front illumination. In order to avoid ITO, a flexible Kapton substrate, which has been sputtered with one layer of **aluminum** and a subsequent layer of **chromium**, is used as initial input in the main process. Masking the foil, the stripes have been **directly patterned**. Then, on the patterned cathode, the process follows as in **ProcessOne**. An improvement in performance was achieved compared to prior similar reports. The study's main aim is to compare the **environmental impact of avoiding ITO** which has been proven by previous studies to be contributing most to EPBT. Moreover,

a recent report by the EU identifies indium as one of the 14 most critical mineral raw materials [23]. The LCA system boundaries include **raw materials production and extraction**, **module processing, and module use**. The functional unit is 1 m² of processed surface area of which 54% is covered by PV modules. The energy mix for Denmark was used for the emissions inventory. For the calculation of the EPBT the assumptions are a constant OPV module efficiency in the range of 1–5%, an insolation level of 1700 kWh/m²/yr and a service lifetime of 15 years. The environmental analysis reveals an **EPBT of about 10 years** due to the high-energy consumption of Al/Cr R2R sputtering and to the relatively low efficiency of the Hiflex OPV modules (1%). An optimization of the active area fraction could easily reduce the EPBT to 5 years. A further enhancement of the efficiency to 5% would give rise to a promising **EPBT of only 1 year**.

The major conclusion that one can draw from this and previous work and analysis, is that OPV seemingly is a promising technology that however will **require significant re-development** before it can be viewed as a technology that solves more problems than it creates. Future developments should therefore seek methods that **do not involve silver, indium, vacuum, or complex processes and should maximize the usage of the processed area**.

2.2.6. Environmental and economic assessment of ITO-free electrodes for organic photovoltaic solar cells

A sixth study by **Emmott *et al.* (2012)** [24] discusses some of the **alternative materials for ITO**, being slot-die coated high-conductivity PEDOT:PSS, a screen-printed silver grid embedded in PEDOT:PSS, slot-die coated silver nanowires, and spray-coated single walled carbon nanotubes. These materials were chosen due to their potential for low cost and low energy manufacture, as well as the availability of detailed information on their manufacture. **Graphene films**, which are mostly deposited using chemical vapor deposition, are **disregarded** as they do not solve the problem of high embedded energy. The study adds **robustness under flexing** to the previously mentioned reasons for replacing ITO. It presents a **life cycle and cost analysis** of OPV devices manufactured using **ProcessOne** but with ITO-free electrodes, making use of data gathered during previous studies [20, 25]. The LCA system boundaries include **embedded energy in all raw materials** used in the fabrication of the electrode as well as the **energy requirements for manufacture**. Energy demands associated with the manufacture of the required equipment as well as transport of the raw materials and the final product are not included in this analysis. An **EPBT and cost per Watt for OPV modules for each alternative** is calculated. The breakdown of the maximum embedded energy and minimum cost per m² for all alternative modules can be found in the appendix (see section 5.7.). It shows that **PEDOT:PSS is the least energy-consuming option**. Additionally, it was also identified as the **cheapest (€/m²) transparent conductor**. On a **cost per Watt basis and for the EBPT**

PEDOT:PSS competes with **silver nanowires** for the top position. The EPBT calculation is based on a cell efficiency of 3%, a performance ratio (PR) of 75% to account for system losses, a photovoltaically active area of the module of 67%, and an annual insolation of 1700 kWh/m². The results show that there is **great potential for reducing both the energy payback time and the cost of OPV modules by replacing ITO** with an alternative transparent conductor.

2.2.7. Cumulative energy demands for small molecule and polymer photovoltaics

A seventh study by **Anctil *et al.* (2012)** [26] assesses the **cumulative energy demand (CED) of 26 different types of OPV** that have been developed over the past 5 years, which include alternative material and structure combinations with efficiencies higher than 3% for small molecules and 4.5% for polymer devices to determine how the environmental impact of OPV has changed as a function of technological progress. Such action is necessary as: (1) the typical BHJ using P3HT-PCBM is not longer a representative of the newer generation OPV devices, and (2) previous reports underestimated the fullerene contribution to environmental impact [27]. The embodied energy is calculated using the **most recent or efficient synthesis methods** to establish the reactant inputs and product yields. With the use of new inventory data, the life cycle energy impact associated with production of both **single junction and multi-junction** architectures has been calculated including **BHJ polymer, planar (P) small molecule, and planar-mixed (PM) small molecule** devices. The study's system boundaries include all processes from raw material extraction and material manufacturing through fabrication of the complete solar cell ('cradle-to-gate'). The functional unit is a 1 Wp solar panel. The process flow for the production of organic photovoltaics and active layer morphologies for polymer and small molecule photovoltaics are given in the appendix (see section 5.8.). The CED for the 26 different types of OPV is shown below in Figure 5.

The **CED per WP** required to fabricate **small molecule and polymer** photovoltaics is shown to be similar, from **2.9 to 5.7 MJ/Wp**. The CED/Wp of small molecule devices is on average slightly higher than for polymer devices, but this is largely because of the lower device efficiencies reported. The CED is on average of **50% less** than for conventional inorganic photovoltaics, motivating the continued development of both technologies. Multi-junctions have a negative effect on polymer solar cells CED, but a positive effect on small molecules. The use of **fullerenes** was shown to have a dramatic impact on polymer solar cells, comprising 18–30% of the CED, despite only being present in small quantities. **ICBA** was evaluated as being less energy-intensive. Increases in device efficiency are shown to only marginally reduce CED for both small molecule and polymer designs. The results in Figure 5 make it clear that **other components in the device are major contributors**, in particular the **ITO sputtering**, which alone accounts for more than 35% of the total CED. Although increasing

device efficiency reduces the contribution from the rest of the device, further reduction in embodied energy will **require reduction of the other components beyond the active materials**.

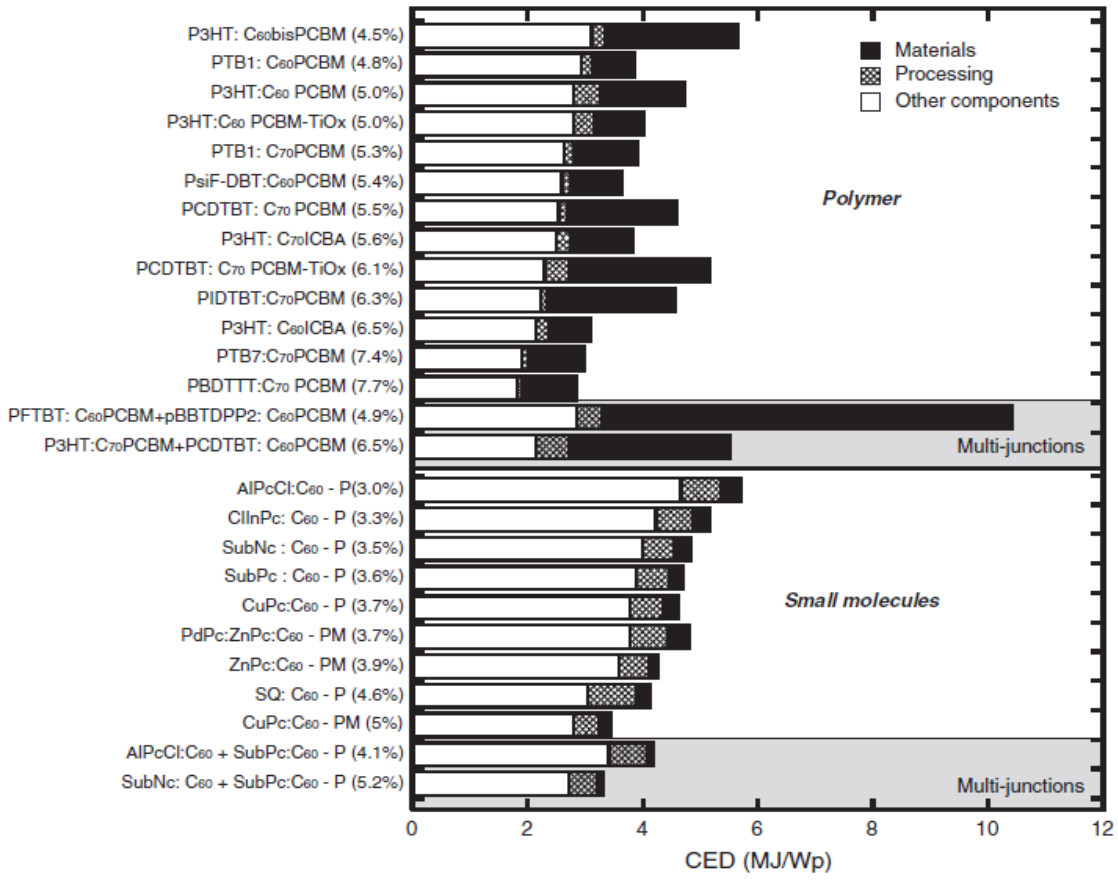

Figure 5: Cumulative energy demand for 26 types of organic photovoltaics [26]

2.2.8. Solar cells with one-day energy payback for the factories of the future

Critical for the success of renewable energy technologies is the time it takes for a given technology to earn back the energy invested in its making and constitution. For the most successful and mature renewable energy sources such as **wind and hydro power the EPBT is in the range of 3–6 months**. The EPBT has been thoroughly investigated for all **PV technologies** already on the market, and ranges between **4.12 and 0.73 years**. In a study by **Espinosa *et al.* (2012)** [28] the LCA methodology is used to direct research and develop a polymer solar cell with exceptionally low EPBT. The LCA system boundaries include direct energy to the **manufacturing process**, direct energy to produce **materials** (primary and ancillary), and **decommissioning**. Transport has been neglected. The functional unit is 1 m² of processed area with 45% of active area. The structure of the modules can be found in the appendix (see section 5.9.). ProcessOne serves as the reference route. The energy needed for manufacturing the materials was computed for **Processes A to K, and for Process Two** and can be found in the appendix (see section 5.10.). The energy needed for the manufacturing steps can also be

found in the appendix (see section 5.11.). ProcessOne is not displayed because it is out of scale. The graphs show that an enormous **decrease in energy is possible**. **Process H** is found to be the least energy-consuming (44.82 MJ_{EPE}) by about a factor ten relative to ProcessOne. Subsequently, when comparing process H with ProcessOne and ProcessTwo a trend of **generally diminishing environmental impacts** (carcinogens, respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels). Nevertheless **PET's** environmental impact was identified as being particularly high for process H, especially in the fossil fuels category. **Further improvements** are identified (e.g. using renewable power instead of the mix, decreasing barrier thickness, increasing substrate width, increasing geometric fill factor, increasing efficiency, increasing lifetime, increasing recyclability and biodegradability, …) and their reduction on EPBT assessed. It was found that very short **EPBT** in the order of **one day** are possible, thus potentially presenting a solution to the current energy gap of >14 TW by year 2050. The **use of renewable energy** is decisive in this context, as it is not possible for all other PV technologies. However, **even when using the most energy-consuming ProcessOne**, **a 10% module efficiency puts OPV in the same range as wind and hydro power**.

2.2.9. Deciphering the uncertainties in life cycle energy and environmental analysis of organic photovoltaics

In a ninth study by **Yue *et al.* (2012) [29]** the life cycle GHG emissions and EPBT of a scalable OPV module in the three cities Chicago, New York and San Francisco, for the current, near-term future (1-2 years) and long-term future (~5years) scenario has been analyzed. Instead of using the deterministic or 'single point estimate' method, a **probabilistic approach** by applying an uncertainty analysis to each of these scenarios using the Monte Carlo simulation method was used with 1 million trials, thereby **quantifying the uncertainty and risk** associated with each scenario. The **solar insolation, power conversion efficiency, transport distance, performance ratio, system degradation rate and lifetime** are considered the uncertain parameters. The assumed input values/distributions can be found in the appendix (see section 5.12.). The percentage active area is fixed but different in each scenario (45%, 67%, 85%). The LCA system boundaries include the energy embedded in **materials**, direct **process** energy and energy for **transport till the vendors' gate** (but transport for raw materials is omitted). The functional unit is defined as 1 m² OPV modules. The finished modules are transported from Phoenix to the three cities mentioned above by truck. The data for the LCI originate from **Espinosa *et al.* (2012)** [28]. From the resulting probability distributions for the EPBT it is observed that an **increase in power conversion efficiency and percentage active area** would largely **reduce the EPBT and its standard deviatio**n. A sensitivity analysis showed that the performance ratio, the efficiency, and the insolation influence the EPBT variance most for the near-term future scenario. From the probability distributions for the **GHG emission factor similar conclusions** can be drawn.

By comparing the proposed OPV technology with four typical silicon-based and thin-film photovoltaics in the aspects of EPBT and greenhouse gas (GHG) emissions, they demonstrate the **great potential of OPV in environmental sustainability**. Furthermore, the probabilistic approach displayed a **wide distribution** for the EPBT and CO_2 emission factor values, rather than squeezing around a single value. This demonstrated the **insufficiency of deterministic analysis**, which would give a false impression of certainty in the outcomes.

3. Conclusions

This report has covered the available literature on the environmental impact, mostly energy payback times (EPBT) and the associated greenhouse gas (GHG) emissions (factor), resulting from at least the materials acquisition and manufacturing stage of polymer and molecular organic photovoltaics (OPV) devices. It is concluded that most literature performing LCAs so far has focused on the impact of the typical bulk heterojunction organic solar cell using P3HT-PCBM as the light absorbing layer deposited on a flexible PET substrate. This does not mean that the obtained results are directly comparable for a number of reasons, being for instance a different system level envisaged (active layer, cell, module, PV system), different input materials used, different synthesis/manufacturing techniques used, different types of production environment studied, different LCA boundaries used, different assumptions on uncertain parameters, and the availability of (correct) inventory data. Nevertheless, the set of results shapes the environmental profile of polymer-based OPV. Viewing this bigger picture, great potential regarding environmental sustainability has been identified (see Table 1). At the same time the LCA methodology has allowed the identification of the technology's (future) bottlenecks.

Environmental sustainability metric	OPV
Overall environmental impact (on a Wp basis compared to mc-Si PV *systems*) [2009]	is 20-60% lower using glass substrates, 80-95% lower using PET substrates
Embedded energy (on a MJ/Wp basis for *modules*) [2010]	compares favorably with mc-Si, similarly with thin film and slightly worse than DSSC
Energy payback time (conditional upon various assumptions for *cells*) [2012]	in the order of 1 day is possible
Depletion of rare metals (conditional upon information available) [2012]	ITO should be replaced from both cost and energetic point of view

Critical for the success of renewable energy technologies is the time it takes for a given technology to earn back the energy invested in its making and constitution. To be sustainable this time must be

shorter than the lifetime of the device. For the most successful and mature renewable energy sources such as wind and hydro power the EPBT is in the range of 3–6 months. The EPBT has been thoroughly investigated for all PV technologies already on the market, and ranges between 4.12 and 0.73 years. For polymer-based OPV it was found that very short EPBT in the order of one day are possible assuming most technological challenges are successfully met and renewable energy was used to power the entire manufacturing process. However, at least as important is that ProcessOne, which is the most cited and closest to an industrial process available in literature, performs equally well as wind and hydro power assuming a module efficiency of 10%, while it still leaves plenty of room for energetical optimization. Environmental impacts (carcinogens, respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels) are shown to exhibit a diminishing trend if energetic optimization is performed.

Nevertheless, the extended LCA results do not state the technology to be sustainable at this moment. They also identify processes that should be avoided (ITO sputtering, vacuum steps, use of certain hazardous solvents and chemicals), processes that should be optimized (usage of the processed area), and potential material constraints (silver, indium). Future developments to and analysis of the technology are therefore needed in our aim for a sustainable energy production.

4. References

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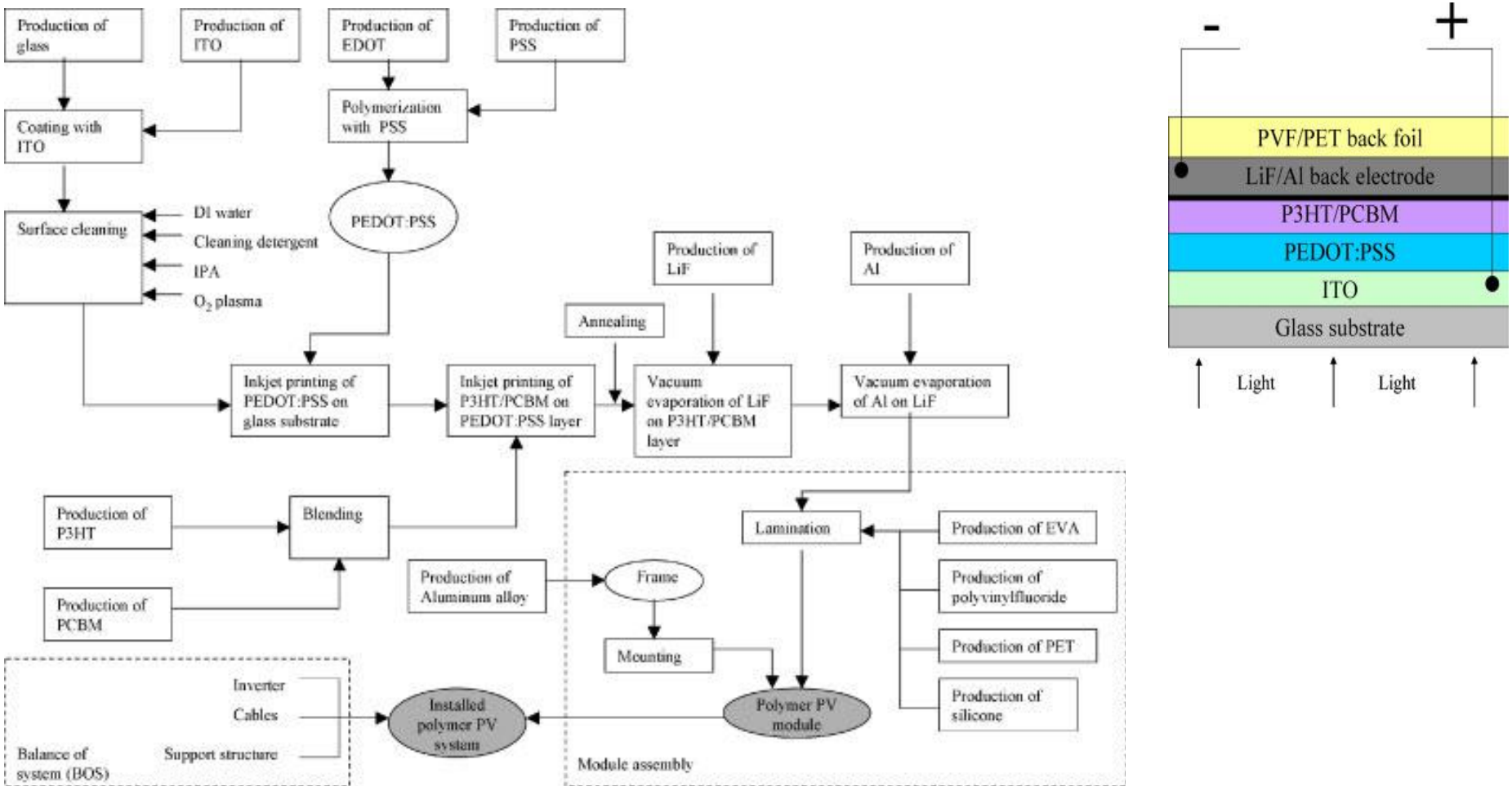
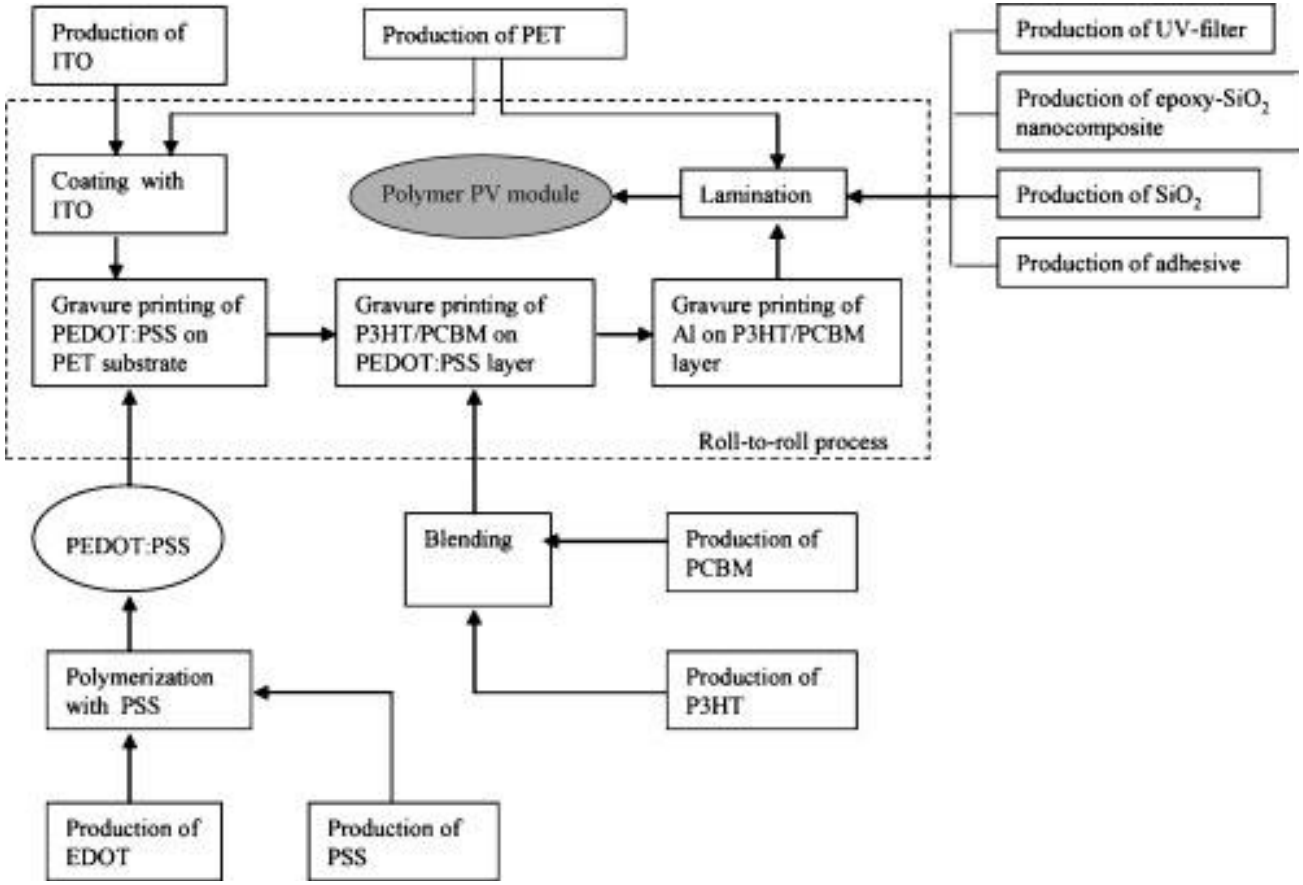
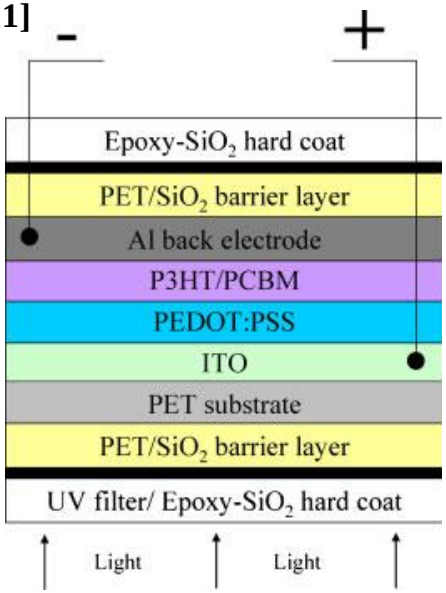
5. Appendices

5.1. Process chains and solar cell build-ups for polymer PV systems on a glass substrate [11]

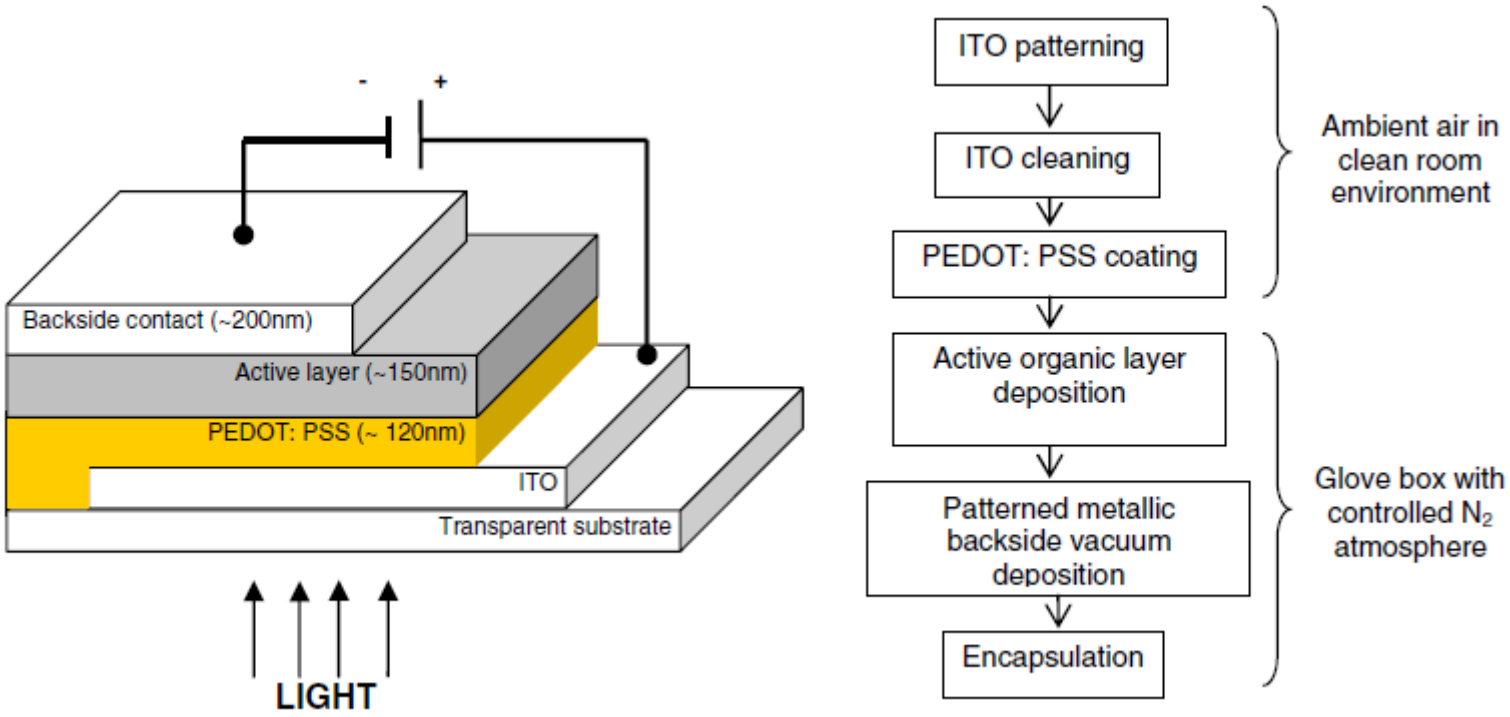


5.2. Process chains and solar cell build-ups for polymer PV systems on a PET substrate [11]

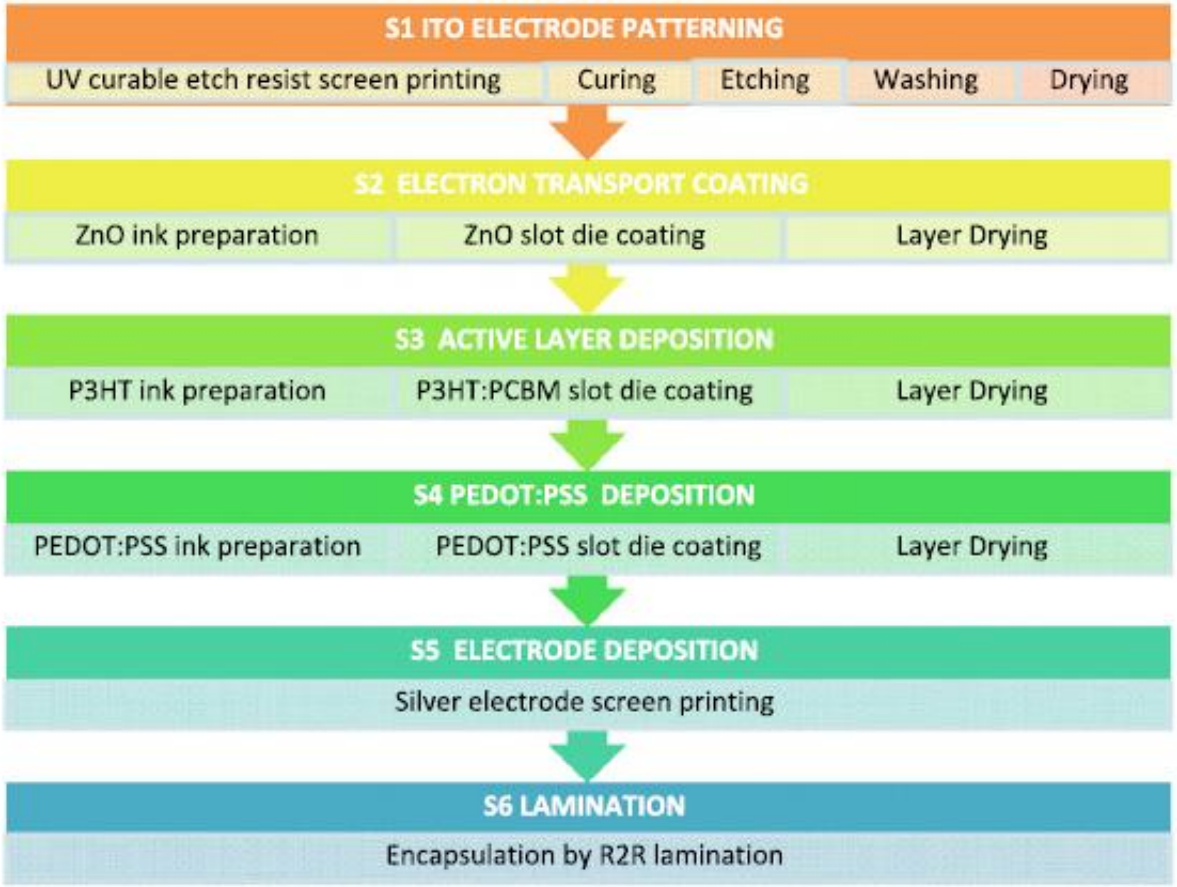




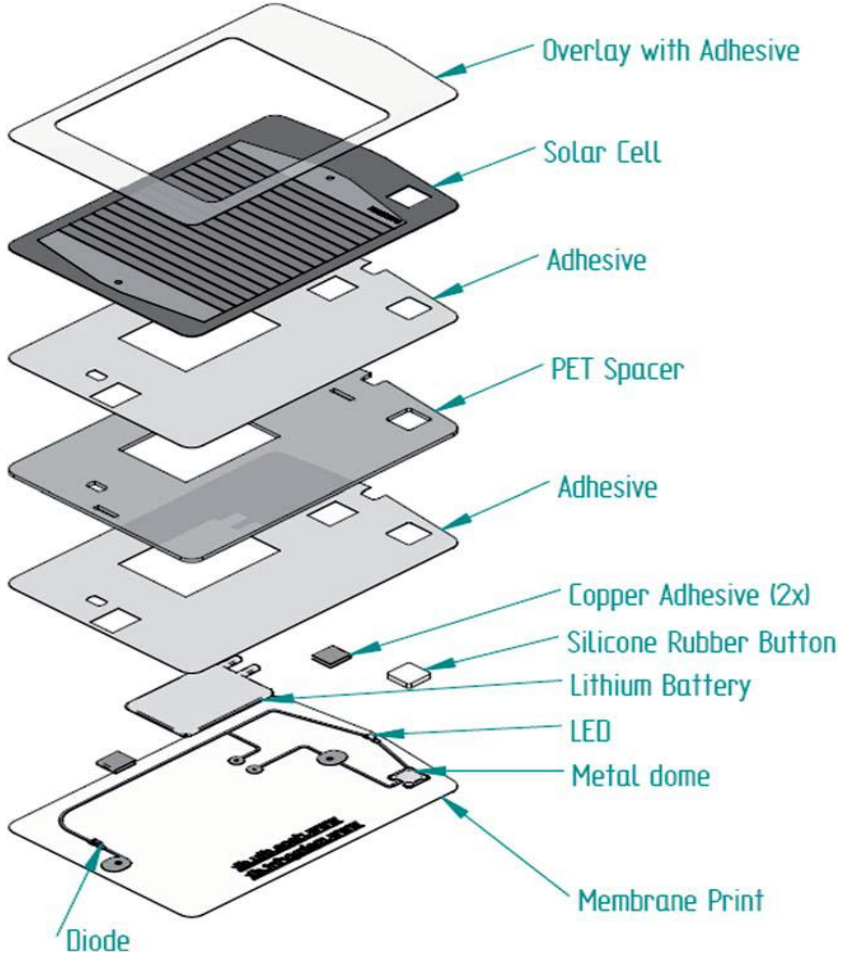
5.3. Scheme for the laboratory processing of polymer-fullerene organic solar cells [16]



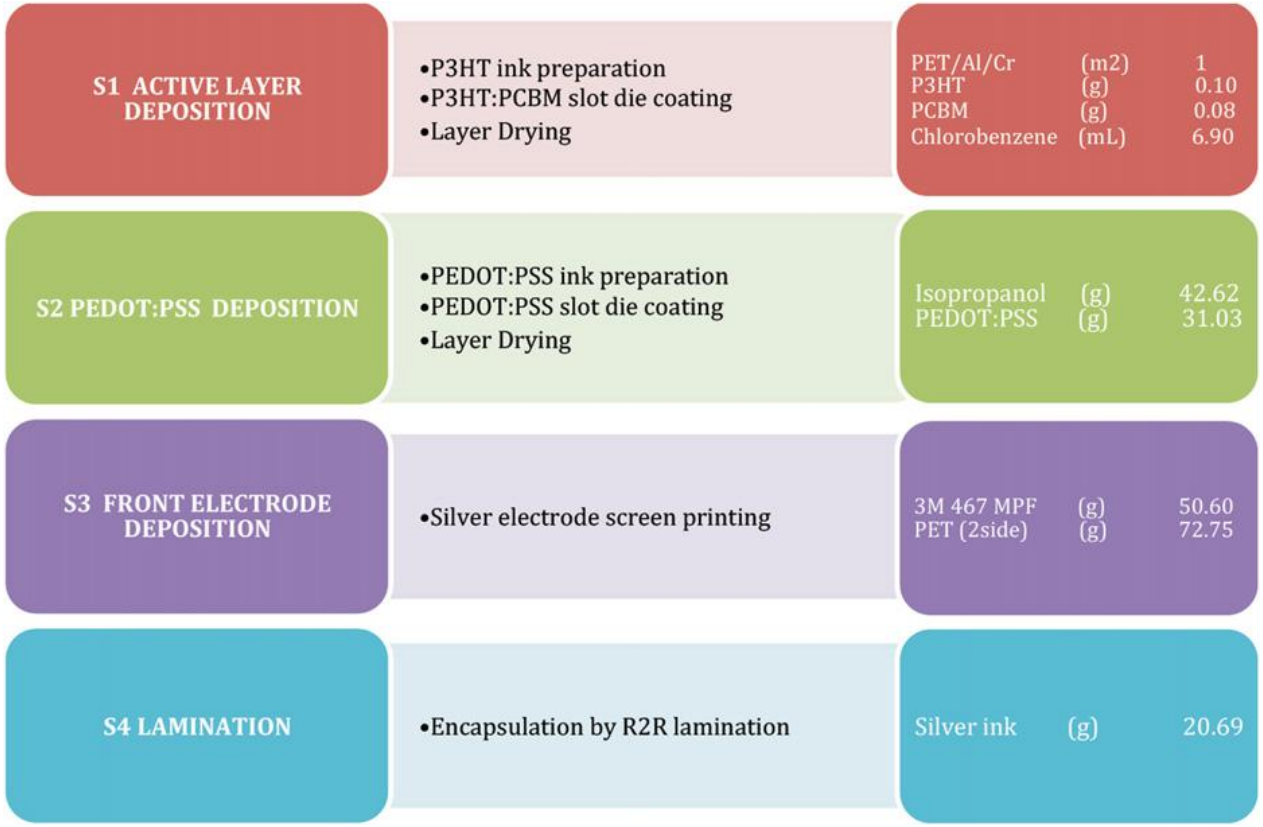
5.4. Steps and substeps during the ProcessOne manufacturing of OPV modules [20]



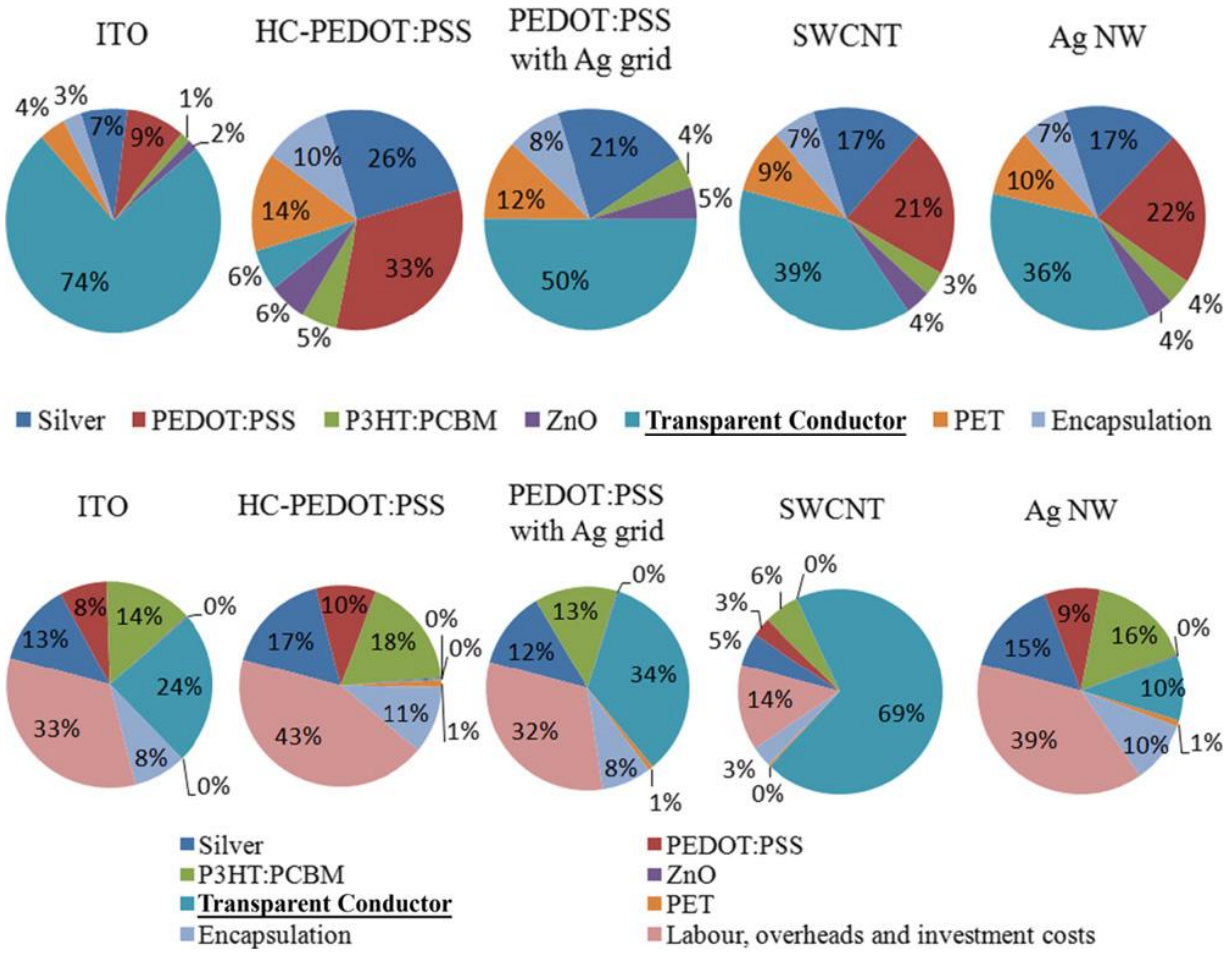
5.5. Cross-section of an organic photovoltaic solar module powered lamp [21]



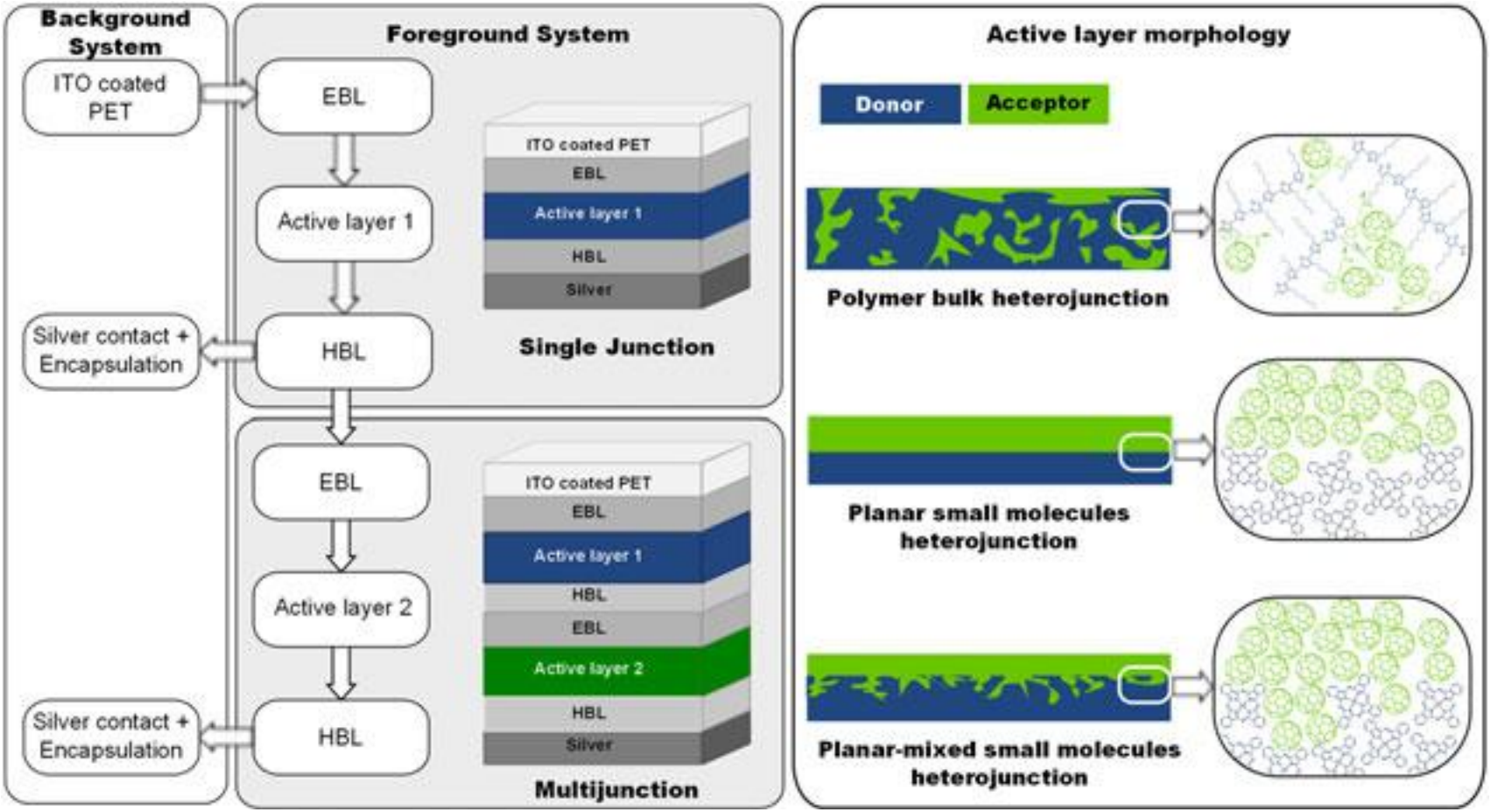
5.6. Hiflex manufacturing process steps and material inventory for 1 m² of processed substrate [22]



5.7. Breakdown of the maximum embedded energy (T) and minimum cost per m² (B) in organic photovoltaic modules using various electrodes [24]



5.8. Process flow for the production of organic photovoltaics and active layer morphologies for polymer and small molecule photovoltaics [26]

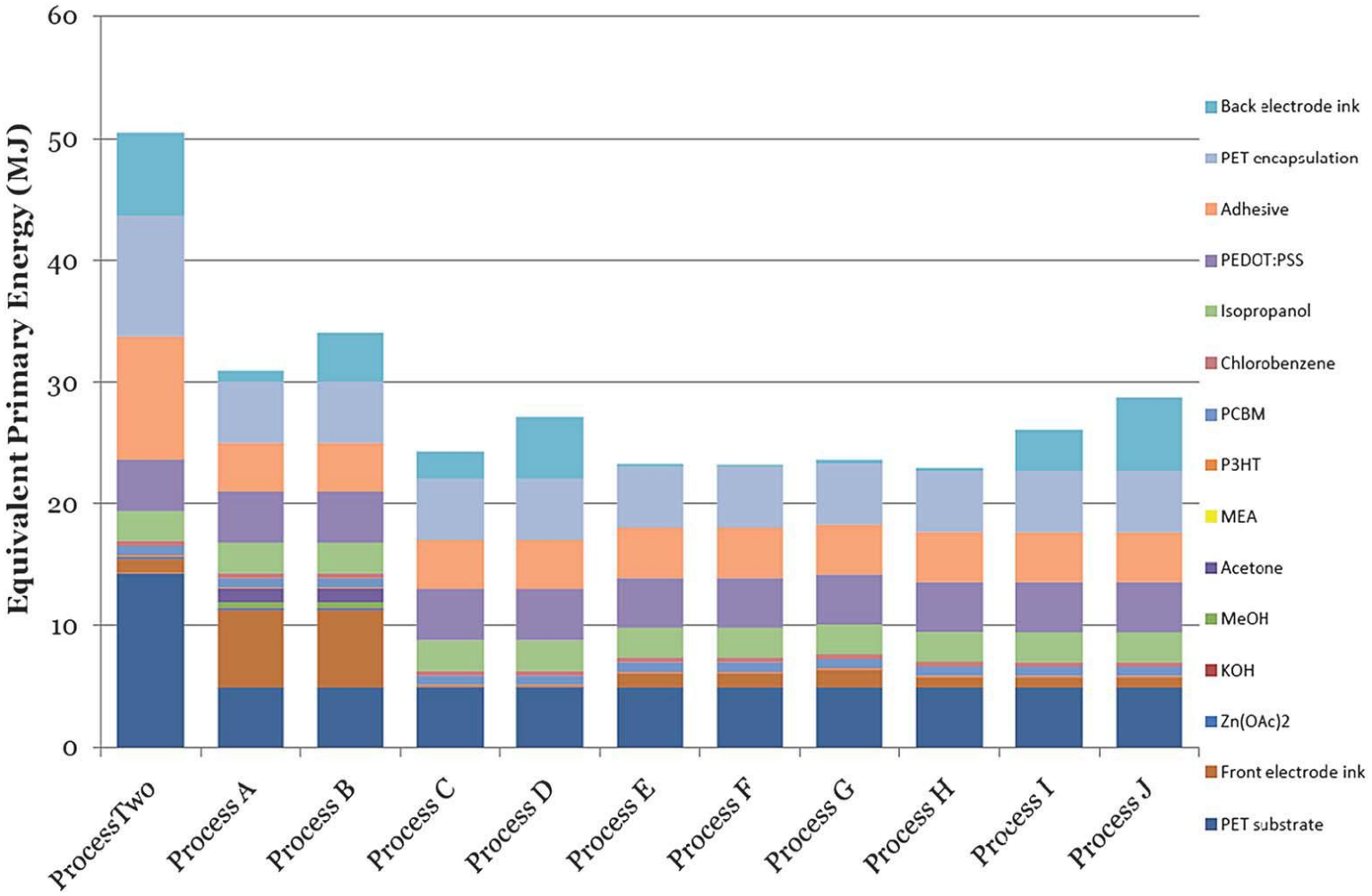


5.9. Layers of the manufacturing routes for producing ITO-free solar cells and the reference route ProcessOne [28]

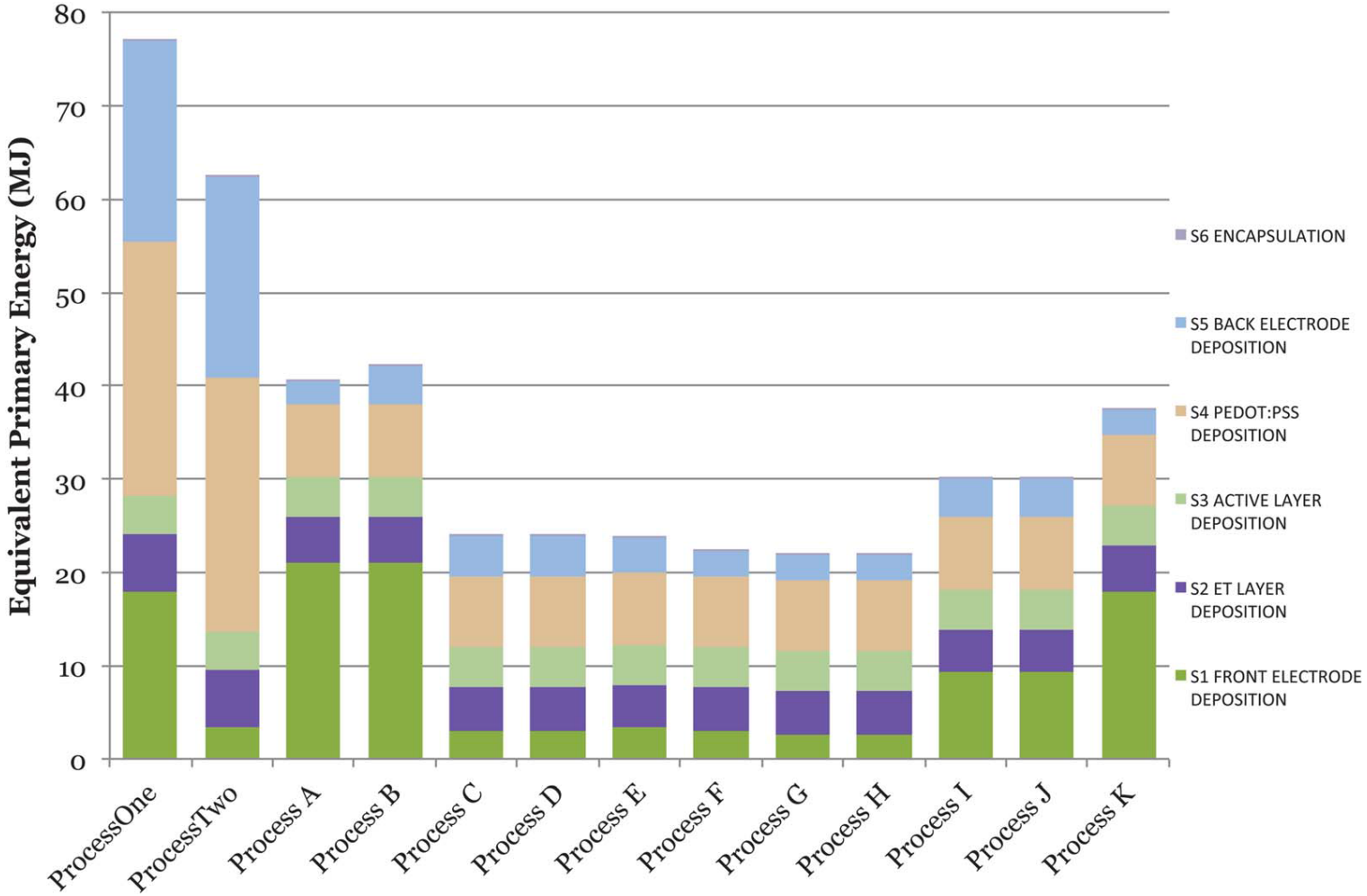
Process Name	Layer					
	1	2	3	4	5	6
A	SD PEDOT:PSS Agfa	SD ZnO np			RSP C GRAPHITE F	
B		SD ZnO np			SP Ag PV 410 F	
C	SD Ag in nBuOH				SP C GRAPHITE F	
D					SP Ag PV 410 F	
E	SD Ag nanoparticles				SD Ag Risø's I	
F		SD ZnO	SD ACTIVE LAYER	SD PEDOT:PSS	RSP C GRAPHITE I	
G	RSP GRAPHITE				RSP C GRAPHITE I	
H					SD Ag Risø's I	R2R LAMINATION
I	SD Graphene				SP C GRAPHITE F	
J					SP Ag Risø's F	
K	ITO	SD ZnO np	SD ACTIVE LAYER aq	SD PEDOT:PSS aq	SD Ag Risø's F	
One	ITO	SD ZnO np	SD ACTIVE LAYER	SD PEDOT:PSS	SP Ag PV 410 F	
Two	SD Ag nanoparticles	SD ZnO np	SD ACTIVE LAYER	SD PEDOT:PSS	SP Ag PV 410 F	

SD stands for Slot Die coating, RSP for Rotary Screen Printing and SP for Screen Printing.

5.10. Embodied energy in the materials per functional unit (m^2) in processes from A to J (MJ_{EPE}) [28]



5.11. Direct process energy (MJ_{EPE}) employed for different steps in the manufacturing of OPV modules [28]



5.12. Monte Carlo input assumptions for the calculation of the EPBT and GHG distribution of the current, near-term future and future scenario [29]

Assumptions	Scenario 1	Scenario 2	Scenario 3
Performance ratio[1]			Normal distribution
Mean		0.8	
Std. dev.		0.1	
Conversion efficiency[1]			Normal distribution
Mean	0.03	0.05	0.08
Std. dev.	0.005	0.005	0.005
Insolation in Chicago ($kW\ h\ m^{-2}\ year^{-1}$)[60]			Normal distribution
Mean		1598.19	
Std.dev.		60.26	
Insolation in NYC ($kW\ h\ m^{-2}\ year^{-1}$)[60]			Normal distribution
Mean		1662.78	
Std. dev.		50.84	
Insolation in SF ($kW\ h\ m^{-2}\ year^{-1}$)[60]			Normal distribution
Mean		1956.51	
Std. dev.		58.87	
Road distance to Chicago (km)[61]			Normal distribution
Mean		2875	
Std. dev.		250	
Road distance to NYC (km)[61]			Normal distribution
Mean		4100	
Std. dev.		300	
Road distance to SF (km)[61]			Normal distribution
Mean		1210	
Std. dev.		200	
Lifetime (year) [1,58]			Normal distribution
Mean		15	
Std. dev.		0.5	
Degradation rate[9]			Gamma distribution
Scale		0.006	
Shape		2	

6. Contact

The author of this report is **Sebastien Lizin**. He is a third year doctoral student at the **University of Hasselt**, faculty of applied economics, research institute the **Centre for Environmental Sciences** (CMK), research group of **Environmental Economics**. His PhD is about **assessing the future market opportunities for organic photovoltaic solar cells** by means of integrated technology assessment. To this end, his main focus has been on a **stated preference valuation** method called discrete choice experiments. Contact details can be found below.

Contact details:

E-mail address: sebastien.lizin@uhasselt.be
Postal address: Agoralaan, Building D, 3590 Diepenbeek, Belgium
Telephone number: +32 11 26 86 96