

# CHALMERS



## Polymer and Concentrator Photovoltaic Technologies - Energy Return Factors and Area Efficiency

*Master's Thesis in the Master Degree Programme, Industrial Ecology*

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Göteborg, Sweden, 2006  
ESA-Report No. 2006:8, ISSN: 1404-8167

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Göteborg, January 2006

Birger & Gustaf

## Abstract

Market diffusion of flat plate crystalline silicon photovoltaic (PV) technology has been induced by economical support schemes and has led to reduced cost per produced kWh electricity. For further market penetration of the PV technology, a continued reduction of production cost is required. Two alternative approaches to achieve this are using less expensive materials or changing the active materials. The technologies of concentrator PV (CPV) systems and polymer PV (PPV) devices represent these two strategies. The potential energy performance of these technologies is studied in terms of the process primary energy requirements for manufacturing, how many times this energy is paid back during its lifetime and as the required land area for electricity generation.

The study is an energy analysis incorporating the inherent uncertainties in technology development. Uncertainties are identified in data acquisition, in design choices, as induced by development and improvement, in performance and by different application scenarios. The future technology alternatives are defined in different ways for CPV and PPV. CPV parameters are derived from existing products and ideas for improvements and PPV parameters from the directions of research.

This study shows that the invested energy in future CPV and PPV is potentially paid back up to about 90 and 170 times, respectively, under Arizona (CPV) and average European (PPV) solar irradiation conditions. However the result is highly dependent on configuration, inventory data and device performance. Thus, for certain design alternatives, data and performance, PPV production energy is far from paid back during its lifetime. For CPV the energy return factor is decreased to about 13 in the least beneficial case.

Area efficiency is studied as the land area requirements for producing a net output electricity of 1 MWh during 25 years. With device efficiencies from 1 to 5 per cent and lifetimes from 1 to 5 years a PPV device requires from 2 to 15 times more area than a p-Si cell, with the same system boundaries. CPVs require about 2 or up to 5 times less area than flat-panel p-Si, depending of inventory data.

Generally, active layer polymers or fullerene production energy requirements are not critical for PPV device energy performance. More important is, with large layer thicknesses, the choice of deposition method. The most energy requiring processes during PPV manufacturing are sputtering and vacuum deposition. For CPV systems, tracker, encapsulation and lenses influence overall energy performance most. However, the tracker is most significant for the result, with a contribution of up to 42 per cent.

*Keywords:* concentrator photovoltaic systems, polymer photovoltaic, area efficiency, organic photovoltaics, PV, energy analysis, environmental assessment, life-cycle assessment, LCA, technology assessment, energy return factor, energy payback, area requirements

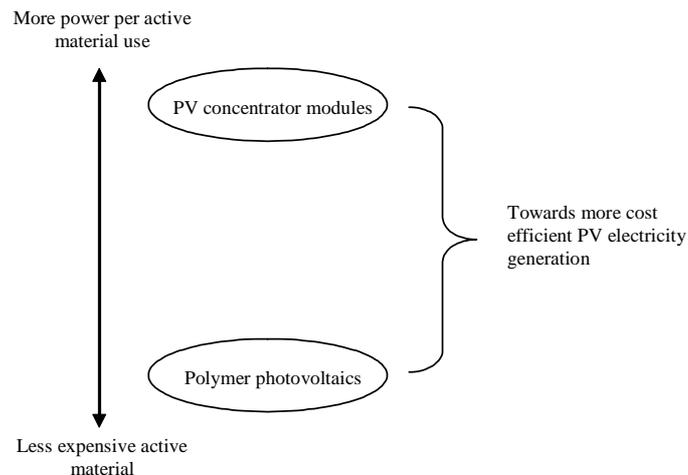
# Table of contents

<b>1</b>	<b>INTRODUCTION AND PURPOSE</b>	<b>10</b>
1.1	QUESTIONS	11
1.2	SCOPE	11
<b>2</b>	<b>METHODOLOGICAL FRAMEWORK</b>	<b>13</b>
2.1	CRITICAL ASPECTS OF PROSPECTIVE TECHNOLOGY LCA	13
2.2	METHODS FOR ANALYSIS	15
<b>3</b>	<b>CONCENTRATOR PV SYSTEMS</b>	<b>19</b>
3.1	GENERAL STRUCTURE	19
3.2	PARTS AND MATERIALS	21
3.2.1	<i>Lenses</i>	21
3.2.2	<i>Cell</i>	22
3.2.3	<i>Heat sink and housing</i>	22
3.2.4	<i>Tracker, foundation and inverter/transformer</i>	23
3.2.5	<i>Possible improvements</i>	24
3.3	PROCESS INVENTORY DATA – SYSTEM 1 AND 2	24
3.4	CRADLE-TO-GATE RESULTS – SYSTEM 1 AND 2	26
3.4.1	<i>Development/Improvement uncertainty</i>	27
3.4.2	<i>Electricity consumption during use</i>	29
3.4.3	<i>Transportation to use</i>	29
3.5	CPV RESULTS	29
<b>4</b>	<b>POLYMER PHOTOVOLTAICS</b>	<b>31</b>
4.1	GENERAL STRUCTURE	31
4.2	SPECIFIC PROCESSES AND MATERIALS	32
4.2.1	<i>Substrate and encapsulation</i>	32
4.2.2	<i>Anode</i>	35
4.2.3	<i>Active layer</i>	35
4.2.4	<i>Cathode and cathode barrier layer</i>	36
4.2.5	<i>Possible improvements</i>	37
4.3	PROCESS INVENTORY DATA	37
4.4	CRADLE-TO-GATE RESULTS	39
4.4.1	<i>Development/Improvement uncertainty</i>	41
4.4.2	<i>Uncertainty induced by assumptions</i>	41
4.4.3	<i>Transportation to use</i>	42
4.4.4	<i>Balance-of-system</i>	42
4.5	PPV RESULTS	42
<b>5</b>	<b>CONCLUSIONS</b>	<b>45</b>
<b>6</b>	<b>FINAL COMMENTS</b>	<b>47</b>
<b>7</b>	<b>LIST OF REFERENCES</b>	<b>48</b>
<b>8</b>	<b>APPENDICES</b>	<b>53</b>
8.1	POLYMER PRODUCTION (LABORATORY SCALE)	53
8.2	VPP PEDOT (LABORATORY SCALE)	53
8.3	CALCULATION OF C <sub>60</sub> PRODUCTION	54
8.4	CALCULATION OF PCBM	54
8.5	CALCULATION OF PLASTIC ENCAPSULATE BARRIER MATERIAL	55
8.6	CALCULATION OF SPUTTER PROCESS ENERGY	55
8.7	CALCULATION OF SCREEN PRINTING	56
8.8	VACUUM EVAPORATION	57

# 1 Introduction and purpose

The solar irradiation striking earth amounts to about 10 000 times the energy society is currently using (Lysen 2003)<sup>1</sup>. Photovoltaic (PV) devices are the only technology that can make use of this potential by directly converting light to electricity. Ambitious subsidy schemes by German and Japanese governments have opened up for roof-top installation niche markets and thereby increased public interest and induced development. Inspired by this similar measures have been taken to reduce the apparent economical disadvantage of the technology. For example, in May 2005 Sweden launched a subsidy scheme supporting overall investments of PV installations on public buildings by 70 per cent. However, compared to traditional energy sources the installed PV power is modest. Even though PV market is increasing, cost reductions through technological development are essential for substantial growth.

Presently the most common PV technology is polycrystalline silicon cells (IEA 2004). Due to the expensive manufacturing cost of the active materials used in this PV technology two strategies for cost reduction are 1) to produce more power per active material or 2) to decrease manufacturing cost of the active material. This can be achieved either by concentrating light from a large solar irradiation area on a small PV cell or by a complete change in materials and manufacturing processes. The technologies of concentrator PV systems (CPV) and polymer PV (PPV) are two extreme representatives of these strategies, see Figure 1.

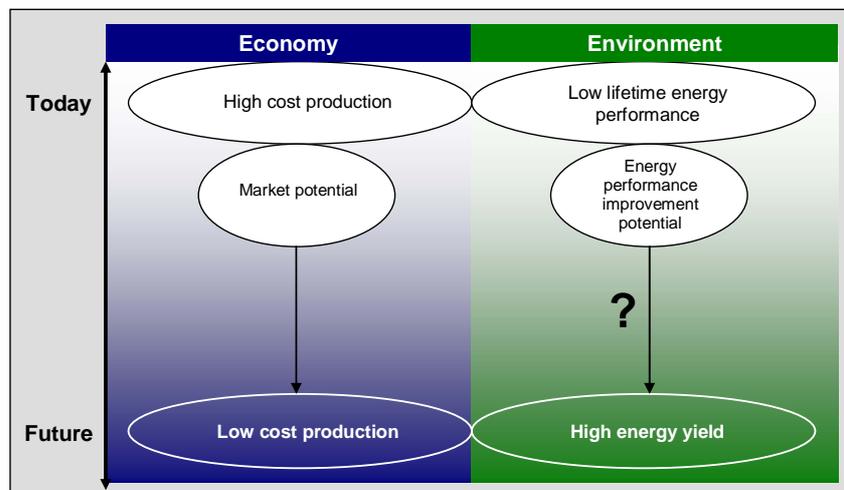


**Figure 1.** PV technology development towards lower cost.

Both technologies' potentials for market penetration in a near future is stated in literature (Wormser & Gaudiana 2003 and O'Neill et al. 2002), but the diffusion process necessitates stakeholders support and sometimes also governmental policy measures. For PV technologies this acknowledgement is vital due to the unfavorable cost structures compared to conventional energy systems (Hayden 2005, Kurtz 2005 and Krebs 2005). Thus, stated potentials need to be thoroughly analyzed to identify important aspects for further development, to inform stakeholders and to guide political actions. In aspects of energy performance, this study introduces this work for PPVs and continues previous work on CPVs (Pehartz & Dimroth 2004).

<sup>1</sup> 3.8 million EJ/year received, as opposed to 400 EJ/year of demand

The energy requirements during manufacturing of a PV system decrease its lifetime energy efficiency. In worst case if an electricity generating device consumes more energy during production than it produces during its lifetime no net output can be considered. For energy technologies intended to become significant elements in a future sustainable society moderate or even high net output energy is required. The net output of a renewable energy technology can also reveal potentials to reduce carbon dioxide emissions, compared to traditional technologies. However, since technology development does not “happen over night” these potentials may not be seen in short perspective performance analysis of present state-of-the-art products. Results must be considered in relation to how young the technologies are and at what state they are analyzed. Since the technologies in this report are in the beginning of their development this study incorporates a number of alternative design solutions in the analysis. These design solutions represent the ideas of further development of present technology or the directions of research.



**Figure 2.** Due to high production cost of the Si-cell materials there exists a clear economic incentive for development of polymer and concentrator PV systems (left side). But are there equally good environmentally motives in terms of energy performance (right side)?

The primary purpose of this study is to analyze the potential energy performance of PPV and CPV systems, see Figure 2. Since prospective technology assessments are rare and fairly difficult to perform, a secondary purpose is to contribute to the theory of such analyses.

## 1.1 Questions

This study answers the following questions for CPV and PPV technologies respectively:

When the technology has realized its potential as represented in present ideas,

- what processes during manufacturing influence the overall energy performance most,
- how many times is the invested energy paid back and
- what are the area requirements for electricity generation?

## 1.2 Scope

This study considers the process energy requirements (PER) consumed during production of a number of imagined and existing design alternatives. Energy from extracting and producing the fuels necessary for the technology production processes are excluded, as well as any

processes for after-use treatment or land filling. The energy embodied in the materials, feedstock energy, is not considered.

The CPV technology is delimited to refractive lens systems with passive cooling. The PPV technology is restricted to devices with an active layer of conjugated polymers or a blend of conjugated polymers and the fullerene derivate PCBM. The “ideas” of further development are defined as the processes expressed as probable in a reachable future by representatives at R&D institutions and in literature.

Geographical boundaries for the technologies’ use phase are defined by the intensity of direct and total solar irradiation. Boundaries for specific production processes of future CPV and PPV products are not specified in inventory analysis. However, when assessing the area efficiency of electricity production solar irradiation conditions for Spain is applied to CPV and European average to PPV.

Production of capital goods, i.e. buildings, machinery vehicles etc. used to produce the products and personnel related energy consumption is excluded Freight transport is considered in sensitivity analysis.

Since the ideas of the technologies’ development are assumed to be realized, time boundaries are defined in aspects of how far development has reached. For some processes, development in terms of energy consumption will probably not change much from current situations, e.g. aluminum and steel production. These processes do not need to be adjusted for CPV or PPV purposes, while other processes are likely to change. This change can either be development from laboratory to industrial scale, e.g. synthesis of conjugated polymers, or adjustment of an industrialized process to fit new purposes, e.g. screen printing solar cells. Thus, inventory data are based on (collected and/or calculated) the situation today, but modified to better match process data under thought commercial conditions.

The functional unit used for inventory analysis is defined as:

*the process energy requirements for production of one watt peak.*

While assessing area requirements the functional unit is changed to:

*one (1) MWh electricity production during 25 years under Spanish conditions (CPV) and European average conditions (PPV).*

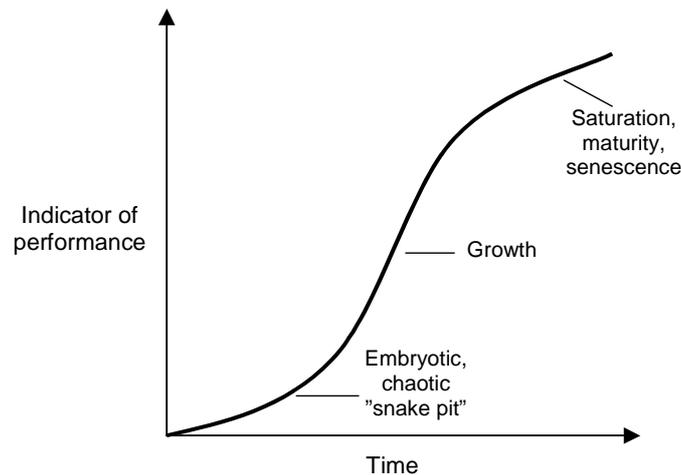
## 2 Methodological framework

This study has the ambitious goal of foreseeing the energy performance of two technologies with very few or no sites of production, only some or none documented performance for the state they are analyzed and, for one of the technologies, without actual areas of application. They are analyzed in a future state where they are assumed to have realized their present ideas of development, thus the analyzed technology design is laboratory state-of-the-art diffused into large scale manufacturing. The inherent difficulties in doing so are several: *How can you specify the materials and processes that are going to be used? What sources of data are found on processes when the production processes of the technology are not fully developed? How can you analyze a whole technology when, at present, not even one product can be presented?* The answers are formulated here as the methodological framework of the study.

### 2.1 Critical aspects of prospective technology LCA

Life cycle assessment (LCA) has developed to be a powerful instrument to evaluate the environmental performance of a product or service at present state. The employed principle is simple; specify the analyzed system with all its individual processes, map all energy and material flows in and out of these processes, categorize them after environmental impact potentials and sum the results. Common categories are global warming potential and potentials for acidification and eutrophication. The principle is also applied in energy analysis, but then only energy flows are considered. The energy circulating in the system can either be dissipated in certain processes or it can be the energy embodied in the materials, called feedstock energy. In principle, feedstock energy is the energy that would be released if the materials were combusted. The result from an energy analysis is therefore expressed in terms of process energy requirements (PER) or, as the total energy, gross energy requirements (GER). The purpose of such studies can be to identify energy intense processes for further development or, as for studies of renewable energy systems, to assess the potential for carbon dioxide (CO<sub>2</sub>) mitigation. This is usually done by subtracting the consumed energy from the produced, translating the resulting surplus energy into CO<sub>2</sub> emissions by a relation between emitted CO<sub>2</sub> per unit energy from an alternative energy production system.

This analysis is tempting to perform on young technologies, to explore its potentials and compare this to present technology. However, in early stages of development a technology consists of a broad range of alternative design solutions. The results from an energy analysis or LCA on a specific product in such a technology would be misleading if it were used in comparison with products within a technology in later stages of development (Sandén et al. 2005). Firstly, the large potential for further development is not necessarily revealed in the results of an analysis on a state-of-the-art product. This potential is inherently different for technologies in different stages of development, see Figure 3. Secondly, with many design alternatives, how can one know if the analyzed product is representative for the whole technology or if the performance of this product is in the lower or higher range of the technology's performance?



**Figure 3** S-shaped stylized technology diffusion. Three general phases of technology development that point out differences in development potentials for technologies within different stages of development. The first phase is characterized by large design uncertainties, the second by fast growth and the last by market saturation. Reproduced from Grübler (1998).

This uncertainty can be dealt with by consideration of extrapolation or cornerstone scenarios (Weidema et al. 2004). In extrapolation scenarios current trends of development, in speed and direction, are assumed to continue into the future. In cornerstone scenarios the system's extremes are estimated to map alternative future states. This study uses a somewhat different approach, which focus on the inherent uncertainties of technology development. A future state is assessed and during this process uncertainties are identified as uncertainties

- in data,
- in design choices (type of materials/processes and material intensity),
- induced by development and improvement,
- in performance and
- in different application scenarios (i.e. geographical site of operation).

Most energy analyses or LCAs analyze a specific system where data on parts of the system are acquired from earlier studies. Different studies generally end up with different results. This can be due to different circumstances and/or different assumptions during calculations.

A specific part or function of a technology can be altered since several design choices are found. For example, encapsulation of a device can be solved in different ways to obtain desired functionality. Type and amount of material and deposition method vary for the available design solutions. When data is acquired for these processes present practice is investigated. However, if these methods are young themselves or if they are developed for a different purpose, further performance improvement are conceivable.

Finally, the actual performance of the devices in terms of efficiency and lifetime is uncertain, but crucial for estimations of the aggregated energy performance of the technology. Furthermore, for PV technologies the actual site of operation is important due to very different solar irradiation at different geographical locations. Not only the amount of irradiance, but also the type is essential to performance. CPVs only function in direct solar irradiation and thus the energy in diffuse light are not utilized.

Hereby, several design choices, data sources and performances are considered and presented as a data range to represent the technology in the analyzed future state.

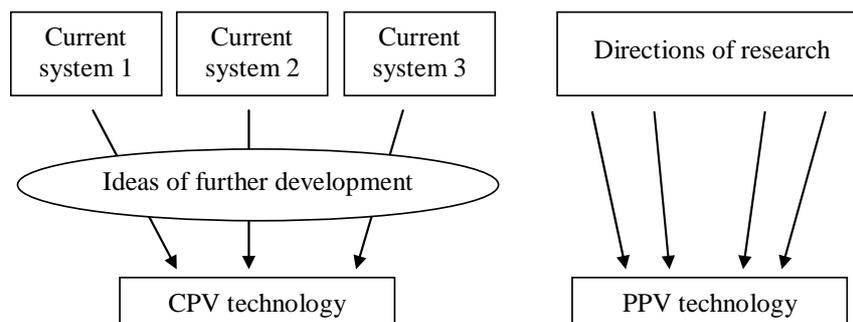
## 2.2 Methods for analysis

Since the young technology consists of a broad range of different products the first step is to define the studied technology by evaluation of literature in the field, by consultation with experts in relevant R&D institutions and by visiting test facilities.<sup>2</sup> PVs have the common concept of being able to produce an electrical current directly from solar irradiation. To distinguish between CPV and PPV narrower concepts need to be developed, i.e. to do this by concentrated solar light or with polymeric photoactive materials.

Three main questions are answered during technology definition:

1. What is the common concept of the studied PV technology?
2. What is the general configuration for products within the technology concept?
3. To define specific materials and processes for large scale production:
  - a. What alternative materials constitute the general configuration?
  - b. How much materials are used?
  - c. What processes could be used for assembling the materials?

These questions are answered in two separate ways, since the uncertainties of the two technologies are different. CPV is a technology where there exists a number of test facilities and where earlier environmental assessments have been performed. Thus, we can acquire information and data from each of these specific products and from the ideas of their further development. For PPV, no products or earlier environmental studies are found, only laboratory research. PPV technology is thereby derived from the directions of research. How these separate approaches for technology definition affects the results is discussed in section 6.



**Figure 4.** Two methods to obtain a technology definition. CPV is derived from existing products and ideas for improvements and PPV solely from the directions of research.

CPV technology is based on Amonix 5-MegaModule (25 kWp), Entech Sunline (860 Wp) and FLATCON (6 kWp). Cradle-to-gate energy analyses are performed on Amonix and Entech Sunline systems while the energy performance of FLATCON is found in literature

<sup>2</sup> PPV R&D institutions: Chalmers University of Technology (Mats Andersson and Erik Perzon), Linköping University (Olle Inganäs), NREL (Sean Shaheen) and Risø National Laboratory (Frederik Krebs).

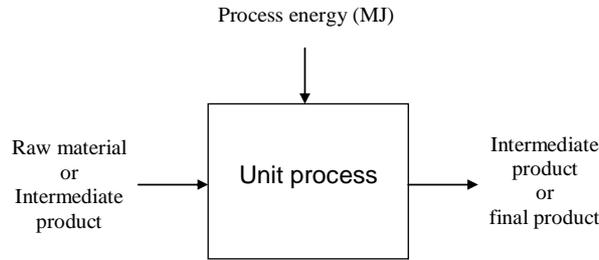
CPV R&D and test facilities: STAR Arizona (Herb Hayden and Thomas E. Fletcher) and NREL (Sarah Kurtz).

(Pehartz & Dimroth 2004 and Bett 2005). Information on Amonix is collected at Arizona Public Service Company (APS) test facility STAR in collaboration with the Environmental Science Department at Brookhaven National Laboratory (Fthenakis & Kim 2005). Data on Entech Sunline are calculated from literature data and from estimations done by the authors at the National Renewable Energy Laboratory (NREL) test facility in Golden, Colorado, USA.

A flowchart is established where every process is depicted as a box called “unit process”, see Figure 5. Every unit process uses heat or electricity. Electricity is assumed to be produced from heat with a conversion efficiency of 0.35. PER,  $Q_{part}$ , of the parts in the general configuration are calculated as the sum over all included unit processes,  $i$ :

$$Q_{part} = \sum_i \left( \frac{m_i a_i}{k_{q,i}} + p_i \right), \quad \dots[1]$$

where  $m$  is the PER for material production (MJ/kg),  $a$  is the material intensity (kg/m<sup>2</sup>),  $k_q$  is a factor for material losses during manufacturing and  $p$  is the PER for the process (MJ/m<sup>2</sup>).



**Figure 5.** In every unit process in manufacturing, energy either convert raw material to an intermediate product or an intermediate product to the final product.

The PER is related to peak power,  $P_{peak}$ , which is a way to rate the PV system performance, measured in Wp and defined as

$$P_{peak} = S_{rate} A k_A \eta, \quad \dots[2]$$

where  $S_{rate}$  is the rating solar irradiation of 1000 W/m<sup>2</sup> for all PV devices but CPV, that have 850 W/m<sup>2</sup>,  $A$  is device or aperture area (m<sup>2</sup>),  $k_A$  is a area utilization factor<sup>3</sup> and  $\eta$  is the cell efficiency.

The influence of transportation to costumer is calculated as the distance,  $D$ , for 1 MJ contribution per watt peak,

$$D = \frac{1}{T_{truck} w}, \quad \dots[3]$$

where  $T_{truck}$  is the primary energy requirements for transportation (MJ/kg km) and  $w$  is the weight per watt peak (kg/Wp).

<sup>3</sup> For CPV:  $k_A=1$ .

The paid back energy is formulated as energy return factor,  $f$ , that is calculated as

$$f = \frac{E_{prod} \kappa^{-1} \lambda}{E_{sys}}, \quad \dots[4]$$

where  $E_{prod}$  is the yearly electricity production (MJ),  $\kappa$  is the heat to electricity conversion factor,  $\lambda$  is the system lifetime and  $E_{sys}$  is the system PER (MJ).

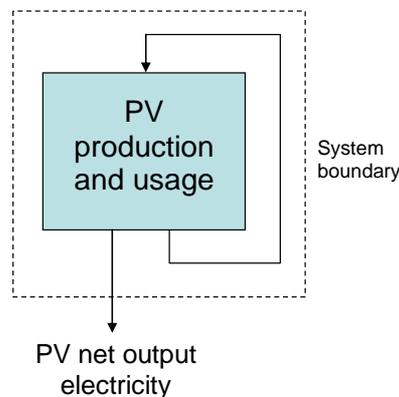
Sensitivity analysis is performed as the system response,  $\Delta$ , to a change,  $\delta$ , in a parameter,  $p$ :

$$\Delta = \frac{SYS((1+\delta)p)}{SYS(p)} - 1, \quad \dots[5]$$

where the function,  $SYS$ , is the analyzed system dependent on the parameter,  $p$ .

Energy analyses like this study often couple renewable energy production to greenhouse gas reduction potentials. To assess greenhouse gas mitigation the electricity flows are allocated by system expansion. Two approaches have been put forward to do this. The first, which is applied in earlier studies by Alsema et al. (2000) and by IEA (1998), convert the primary energy requirements to carbon dioxide emissions and distribute them over the produced electricity as i.e.  $\text{gCO}_2/\text{kWh}$ . This conversion is done by assumption of a utility system that produce the electricity consumed during manufacturing. The value is compared to other energy sources. In IEA (1998)  $\text{CO}_2$  abatement is further calculated in different scenarios for technology market penetration and for different energy systems (e.g. combined cycle gas turbines – coal – average electricity mix) that are displaced by the produced electricity.

The second approach (net output) was introduced by Jonasson and Sandén (2004) to better suite prospective studies on energy systems when a large technological change is considered. Here, the energy required for production is taken from the produced energy, see Figure 6. This is reasonable since the electricity mix in the background system is changed over time and is, in the analyzed state, assumed to hold a significant share PV generated electricity.



**Figure 6.** In the net output approach part of the produced electricity is assumed to be used for producing the PV device itself.

The functional unit is changed from “produced electricity” to “electricity available for other purposes than production of the device itself”. Consequently, for PV the net output approach gives zero carbon dioxide emissions per produced unit energy and, instead, the amount of produced electricity is decreased, or put in other words, the device efficiency is changed. This simpler formulation avoids discussion of selecting the correct electricity production system.

One of the restrictions for production of “clean” PV energy is area limitation, which induce a discussion of area efficiency. This study translate the net output to land area energy efficiency as the area intensity,

$$I_A = \frac{A_{land}}{Q_{sys}(f-1)} \times \frac{\lambda}{25}, \dots [6]$$

where  $A_{land}$  is the device land area for PPV or the necessary land area for CPV,  $Q_{sys}$  is the PV system’s total PER and the factor, 25, is the number of years of electricity generation. Area efficiency is calculated at a solar irradiation corresponding to Spanish conditions for CPV and European average for PPV.

### 3 Concentrator PV systems

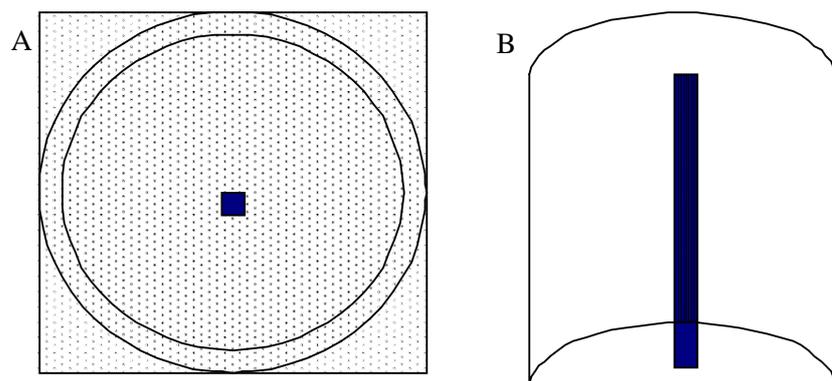
A general overview of the technology of CPV is given followed by a more detailed description of the parts and materials used in the three analyzed CPV systems. For system 3 an earlier energy analysis is found in the literature (Peharz & Dimroth 2004). In section 3.3, additional cradle-to-gate inventory data for system 1 and 2 are described. Results are then presented both for current systems configuration and performance and for the systems with probable future improvements.

Subsequently, results for all three systems are formulated as the overall energy performance for the future CPV technology. This is done for different performance and application scenarios. Finally, the area requirements for producing 1 MWh electricity are presented.

#### 3.1 General structure

The variety of ways for concentrating light that is found in CPV systems all have a general composition of refractive or reflective lenses. These lenses concentrate light on the cells that convert photon energy to electricity. Size and number of cells, magnitude of concentration, focus method and sun-tracking strategy differ between systems. This study considers refractive CPV systems, where light is focused through a lens.

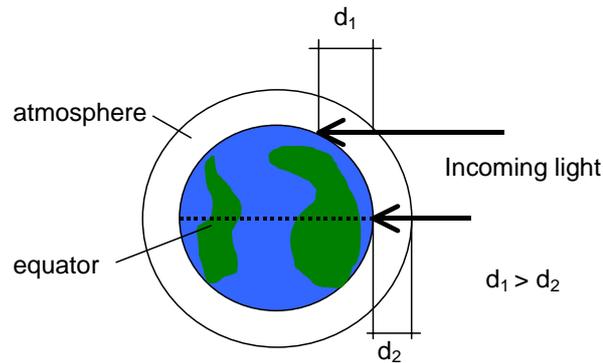
CPV systems using refractive lenses may either focus light point wise or linearly.<sup>4</sup> Point focus is obtained by refracting light down to a small active cell area below the centre of the lens, see illustration A in Figure 7. To focus correctly the incoming light has to be perpendicular. Therefore these systems necessitate a two-axis tracker to follow the sun over the sky. A linearly focusing lens refracts light down to a cell string with an arc shaped lens, see illustration B in Figure 7. With a perfect lens, linear refractive CPVs would only require one-axis trackers since light is refracted on a cell string instead of at a single point. However, linear, arc shaped, lenses have had problems with optical aberrations when refracting light not normal to the lens (Swanson 2003). Both point and linear focusing lenses are possible options for concentrating media and since no R&D representatives have indicated development towards one-axis tracker systems, only two-axis trackers are considered in this study.



**Figure 7.** A. illustrates a point focusing lens with the cell placed in the center below the cell. B. illustrates an arc shaped line focus lens with a line of cells below the lens.

<sup>4</sup> The most common lens are Fresnel lenses where the design enables fabrication of large sized lenses with short focal length, without the weight and volume which would be required for a lens with conventional design.

CPVs can only utilize direct solar irradiation and not the diffuse light that has been scattered in the atmosphere. The amount of diffuse light varies with geographical location, less near the equator and more at the poles, see Figure 8.

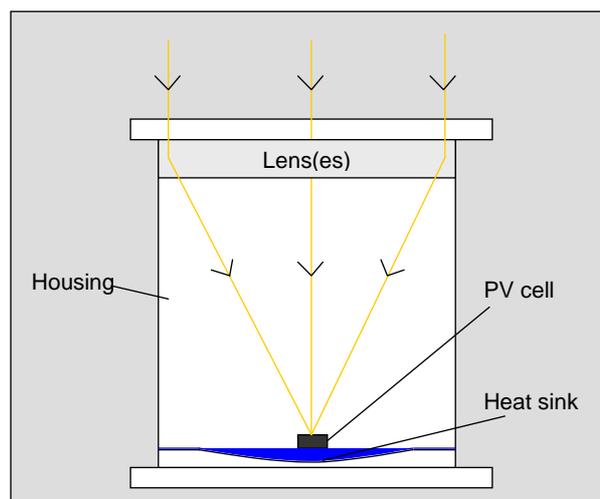


**Figure 8.** At the poles light has to travel a longer distance  $d_1$  than at the equator  $d_2$ , the probability of scattering a photon is also larger.

Tracker design is crucial to make concentration worth the effort. Trackers are considered to be the “Achilles heel” of the system since they rely on old-fashioned mechanical technology (Swanson 2003). Trackers need to be rigid enough to sustain, sometimes large, wind loads.

The surplus solar energy that hits the semiconductor but is not converted to electricity will produce heat. Since increased heat reduces cell efficiency (Swanson 2003), heat needs to be transported away from the cell. There are two types of heat sinks, either with or without an active cooling system. Active systems are generally more complicated, with a cooling liquid media circulating in the system, but they render the possibility of utilizing the produced heat for other purposes. However, only passive cooling systems are considered in this report.

The general structure of CPVs consists of lens, cell, heat sink, housing, tracker, foundation and inverter/transformer, see Figure 9.



**Figure 9.** A refractive CPV section. Multiple sections are put together into a module that together with tracker, foundation and inverter/transformer constitute a whole system. Tracker, foundation and inverter/transformer are not displayed in figure.

### 3.2 Parts and materials

Table 1 presents the type and amount of materials used in the three analyzed systems.

**Table 1.** A compilation of type and amount of materials used in the three studied systems.

Material intensity	System 1		System 2		System 3	
	Material	Data unit	Material	Data unit	Material	Data unit
Lens	Acrylic	880 kg	Acrylic	28 kg	Silicone rubber	n.a.
Cell	Monocrystalline	0.7 m <sup>2</sup>	Monocrystalline	0.14 m <sup>2</sup>	III-V multi-junction	n.a.
Heat sink	Aluminum	408 kg	Aluminum	32 kg	Copper	n.a.
Housing	Galvanized steel	4865 kg	Aluminum	67 kg	Glass	n.a.
Tracker	Galvanized steel	9447 kg	Galvanized steel	177 kg	Zinc steel	n.a.
Motor	Electrical	2 hp	Electrical	1 hp	n.a.	n.a.
Actuators	Hydraulic	3 e.a.	n.a.	2 e.a.	n.a.	n.a.
Foundation	Concrete	5124 kg	Concrete	362 kg	Concrete	n.a.
Inverter	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Transformer	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

*n.a. not available*

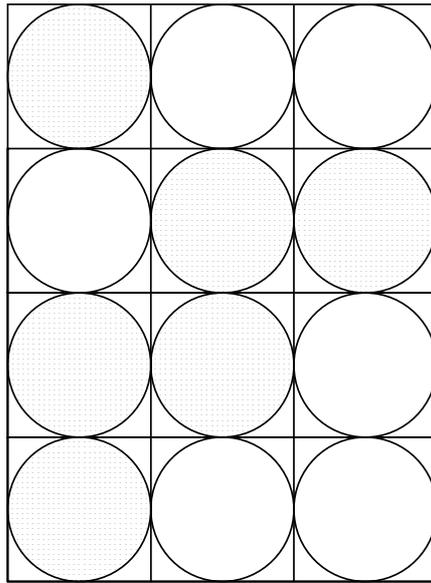
#### 3.2.1 Lenses

Two types of lens material are used, acrylic in system 1 and 2 and silicone rubber in system 3 (Peharz & Dimroth 2004). Acrylic, PMMA, is the most common material for refractive lenses (Swanson 2003). This material is sensitive to precipitation and dust, however when combined with UV stabilizers, acrylic has shown acceptable weatherability (Swanson 2003).<sup>5</sup> System 1 and 3 use flat shaped lenses and system 2 arc shaped. Both lens types have a thickness of 4 mm. The flat lenses are usually molded to form a large unit holding several lenses (Peharz & Dimroth 2004), see Figure 10. Several units are combined in a larger module. A third material, glass, which has better long-term durability than PMMA has been mentioned as an alternative (Hayden 2005), but is at present only used in laboratory devices (Swanson 2003). Development of Fresnel lens production technology has made high yield production possible (O'Neill et al. 2002).

Concentration ratio is dependent on lens technology and focal distance. System 1, 2 and 3 concentrate light 250, 21 and 500 suns, respectively.<sup>6</sup> This concentration can be increased by other or additional lenses. When two lenses are combined, the secondary lens is not as sensitive to weather conditions as the primary, since it is encapsulated in the housing. This opens up for alternative materials and thereby other processing methods. A future alternative to high concentrations, i.e. above 400 suns, is mini-concentrator modules. They consist of silicone rubber that is stretched out to form the final thin lens. These concentrators have so far only been used in space, but have recently been tested in terrestrial conditions. The lenses have a concentration ratio of 8.5 suns (O'Neill et al. 2002).

<sup>5</sup> A UV stabilizer protects acrylic exposed to light from long-term degradation (Norquay Technology Inc.2005).

<sup>6</sup> One sun is the intensity of ordinary sunlight.



**Figure 10** Twelve lenses mould to one unit. Several units may than be added to a larger module.

### 3.2.2 Cell

The cells used in system 1 and 2 are monocrystalline (m-Si) silicon cells. The point focusing systems, 1 and 3, have a cell area of just a few square centimeters. The cells are four centimeters wide in the line focusing system 2 (O'Neill et al. 2002). Modern CPVs use III-V semiconductors to increase performance (Kurtz 2005 and Hayden 2005).<sup>7</sup> III-V single-junction cell efficiencies are only slightly higher than the best silicon cells.<sup>8</sup> However, it is relatively easy to produce more complex III-V multijunction structures. The added complexity in multijunction cells increases production energy requirements. This disadvantage is compensated by both increased efficiency and higher concentration ratio, resulting in less cell area per watt peak.

Compared to silicon cells, the multijunction cells that are used in system 3 require a secondary encapsulation. This material tends to turn yellow under the, for III-V cells, required high concentration ratio (Kurtz 2005).

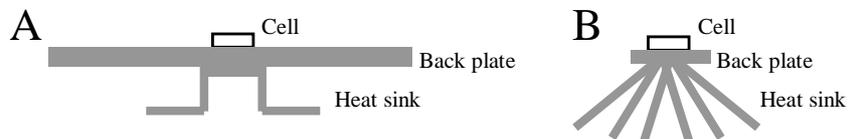
In calculations, the III-V multijunction cells are assumed to have no degradation of efficiency during lifetime.

### 3.2.3 Heat sink and housing

The systems are passively cooled. A natural air flow runs through the metal fins that are deposited on the system back plate, where the cells are connected. Fin design differs between systems. Point focus systems use smaller fins due to larger back plate per cell area, see Figure 11. For the different design alternatives, heat sinks are made of aluminum or copper.

<sup>7</sup> III-V semiconductors are made of elements from third and fifth groups of periodic table of elements.

<sup>8</sup> A single-junction cell consists of only one active layer. A multijunction cell consists of several active layers.



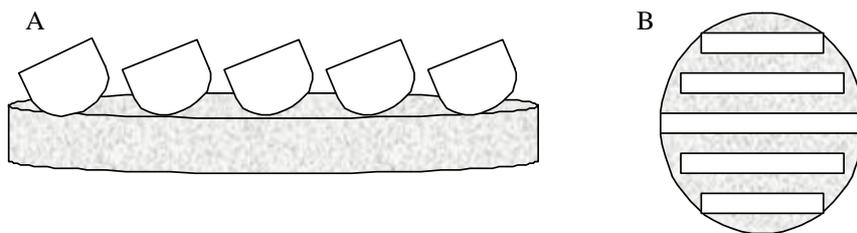
**Figure 11.** Two types of heat sinks. A. show the heat sink used in system 1 and B. show the heat sink used in system 2.

The housing encapsulates and protects the interior cells. The housing materials in system 1, 2 and 3 are made of galvanized steel, aluminum and glass.

### 3.2.4 Tracker, foundation and inverter/transformer

All three systems use two axis trackers with one vertical pipe holding one horizontal pipe where the module is attached. The trackers are made of galvanized steel. To track the sun in different directions, trackers use electrical motors and two to three actuators. Systems with erected trackers have greater losses than systems with better aerodynamics. At a certain amount of wind these systems need to be turned into a safe horizontal position giving no generation of electricity.

One technical solution, promising in terms of wind loads, is the flat, ground mounted, tracker shown in Figure 12 (Pyronsolar 2005 and Kurtz 2005). This two axis tracker has a movable, circle shaped bottom with line focus modules placed above.



**Figure 12** A. illustrates tracker system from side. B illustrates tracker from above. The illustrations A. and B. are not equal in scale.

In all three systems, the foundation is made of concrete. No reinforcement bars are necessary, instead the pipe of the erected tracker function as reinforcement. Increasing system size and thereby also pipe size, the amount of concrete used per watt peak is decreased, since the interior of the pipe is hollow.

To deliver alternating current (AC) single systems need one inverter and one transformer. When combining several systems it is possible to use one inverter for four systems and one transformer for up to fifteen systems (Fletcher 2005).

### 3.2.5 Possible improvements

The following processes are considered in section 3.4.1 since they are regarded as young with large potential for further development.

High efficiency III-V multijunction cells have been developed for more than a decade (Kurtz 2005). Due to higher efficiency but also higher prices than silicon cells only space niche markets have been attractive. To achieve acceptable cost for terrestrial use of III-V multijunction concentration of 400 suns or greater may be needed (Olson et al. 2003). This indicates that future CPV systems have replaced silicon cells with III-V cells.

For all presented tracking systems process energy reduction is feasible through increased system size, i.e. more modules mounted to the same, or a slightly modified, tracker (Fletcher 2005 and O'Neill et al. 2002). It is possible that larger tracker modifications can reduce material consumption and losses due to weather sensitivity, see e.g. Figure 12.

### 3.3 Process inventory data – system 1 and 2

Figure 13 displays the general processes involved in production of system 1 and 2. Inventory data are collected and validated for all processes.

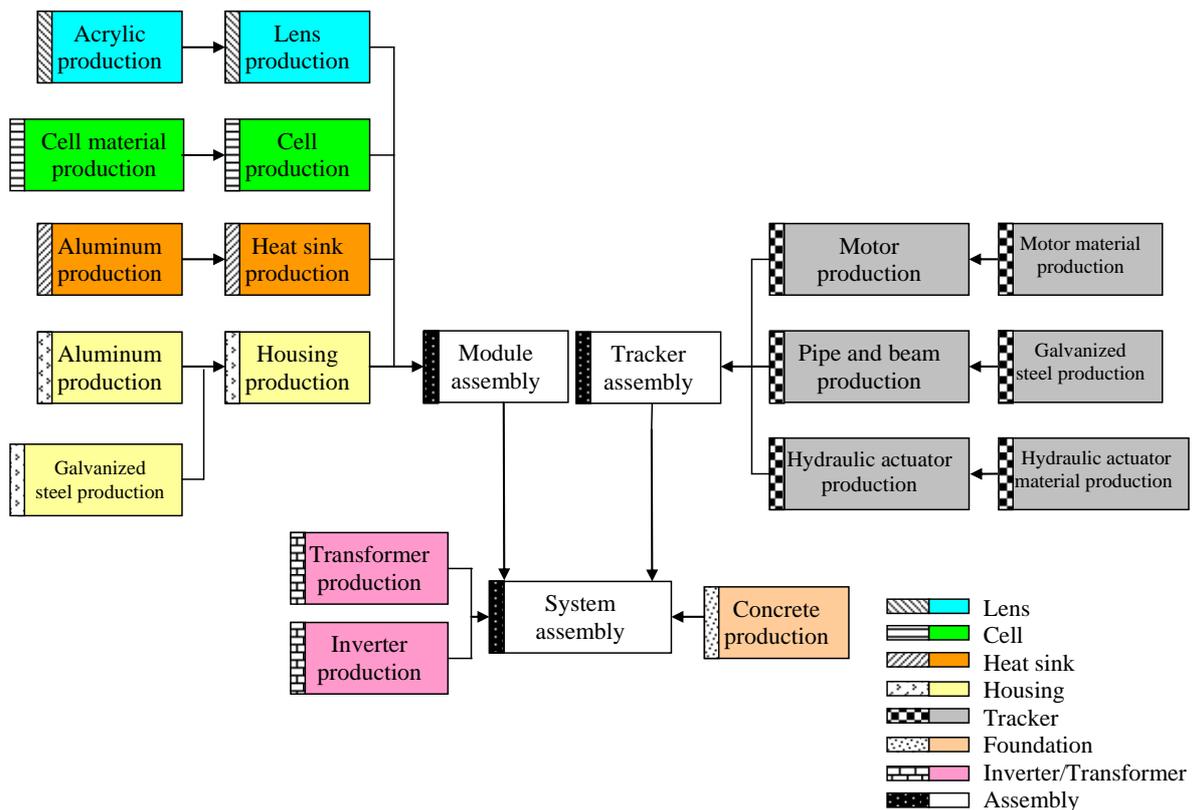


Figure 13. General flowchart over production processes of CPV systems.

**Table 2.** A compilation of all process inventory data used.

Process	Low data unit	electricity	Reference	High data unit	electricity	Reference
Lens, moulding and material prod.	71 MJ/kg	10%	Plasticseurope 2005	n.a.	n.a.	
Aluminum production	* MJ/kg	n.a.	BUWAL 250 1996	81 MJ/kg	75%	Sunér 1996
Steel production	11 MJ/kg	29%	Sunér 1996	* MJ/kg	n.a.	ETH-ESU 1996
Concrete production	0.81 MJ/kg	25%	Björklund & Tillman 1996	n.a.	n.a.	
Electrical motor production	672 MJ/kW out	n.a.	ABB Automation, 1997	n.a.	n.a.	
Monocrystalline production	5875 MJ/m <sup>2</sup>	n.a.	Alsema et al. 2000	* MJ/m <sup>2</sup>	n.a.	ETH-ESI 1996
III-V cell production	198094 MJ/m <sup>2</sup>	n.a.	Peharz & Dimroth 2004	n.a.	n.a.	
Inverter production	1 MJ/Wp	n.a.	Baumann 1997	0.72 MJ/Wp	n.a.	Baumann 1997
Transformer production	0.36 MJ/Wp	n.a.	Baumann 1997	n.a.	n.a.	
Assambly of module	51 MJ/system	100%	APS 2005			

n.a. not available

\* not an open source

Energy data used for the unit processes *acrylic production* and *lens production* are both assumed to be synthesis of polymethyl methacrylate sheet, PMMA-sheet, (PlasticsEurope 2005). They present their inventory data divided in fuel production and delivery, energy content of delivered fuel, energy use in transport and feedstock energy. The processes valid for this report are for energy content of delivered fuel and energy use in transport. PMMA beads can be converted to sheets either by extrusion or by dissolving the polymer in a suitable solvent, pouring the solution into a mould and then allowing the solvent to evaporate (casting). Data have been obtained for both processes and an average of the two is used. Masses of fuels have all been converted to energy units using the gross calorific values. The electricity share of the total primary energy is 10.4 per cent.

Energy data for *aluminum production* is gathered from two different sources. The raw material, used for the electrolysis in the production of virgin aluminum, is aluminum oxide imported from Jamaica or Guinea. The production is done at Hydro Aluminum in Karmøy, Norway. The plant uses two different technologies for the refining of aluminum oxide, the older Söderberg process and the newer Prebake electrolysis. Masses of fuels have all been converted to energy units using internal parameters only. It is a cradle-to-gate analysis (M. Sunér 1996).

The aluminum production from scrap is done at Gotthard Aluminum in Älmhult, Sweden. It is a cradle-to-gate analysis where the cradle is the point of extraction of raw materials from the crust and the gate is the point directly after the gate of the factory. In the study, aluminum scrap is treated as an inflow not followed to the cradle. When energy requirements for production of 50-50 virgin and scrap aluminum are calculated data from virgin and scrap aluminum are used. The electricity share of total primary energy is 75.4 per cent.

Low data, see Table 2, for production of aluminum ingots is from 50 per cent virgin aluminum and 50 per cent scrap. The scrap is produced by re-melting and casting of plain scrap from production waste or plain post consumer scraps. Data for virgin aluminum are based on 40 per cent production in Canada and 60 per cent production in Western Europe. The cradle is the point of extraction of raw materials from the crust and the gate is the point directly after the aluminum ingot is produced (BUWAL 250, 1996). No information about electricity share is found. No information of production of heat sink and housing from aluminum is found. It is however considered as small compared to aluminum production and is not included in analysis.

Energy data for *steel production* is acquired from two different sources; both have listed energy data for production of low recycling rate. The production of steel that requires the lowest amount of energy is done at SSAB Tunnsplåt, Sweden. Virgin raw material is mainly

used in the form of iron ore pellets. Virgin scrap is added to cool and to contribute with additional iron. The carbon contents of this steel should be less than 2 per cent (Sunér 1996). The electricity share of total primary energy is 75.4 percent. The higher production value for steel has an average composition of low alloy steel: 93 per cent converter steel, 5 per cent electrosteel, 1 per cent chromium and 1.25 per cent manganese. This is a cradle-to-gate analysis. (ETH-ESU 1996). No information about electricity share is found. These values are used as approximations for galvanized steel. The probably higher energy values for producing galvanized steel rather than conventional steel are still in the range of our two values.<sup>9</sup> The energy requirements for housing production and pipe and beam production are not considered.

Energy data for **concrete production** is gathered from one source. The main contents, 70-90 percent, are aggregates, i.e. gravel or crushed rock, and the rest is mainly cement. A very small part of additives are to achieve appropriate workability. The main energy use is located at the production of cement (Gillberg et al. 2001). The concrete production is ready mixed concrete, K30. The ready mixed concrete is mixed in a factory and then transported out to the site, normally by a truck. Data is from cradle-to-gate where the cradle is the point of extraction of raw materials from the nature and the gate is the point directly after the gate of the ready mixed concrete factory. The use and the disposal are not considered (T. Björklund et. al, 1996:8). The drilling equipment used for ground preparation is not included.

Energy data for **production of an electrical motor** is acquired from one source. Data are taken from an environmental product declaration for a 1.1 kW motor. It covers all environmental aspects for extraction and production of raw materials, manufacturing of main parts and assembly of the motor. Values are based on calculations when the lifetime is 15 years and operating 5000 hours per year (ABB Automation 1997). No information about electricity share is found.

Energy data for **monocrystalline silicon production** is gathered from two sources. Production of solar cells includes purification and etching of the wafers. Afterwards wafers are endowed with phosphorus and after further etching processes, front and rear contacts are printed (ETH-ESU 1996 and Alsema 2000).

Energy data for **assembly of module** is estimated in collaboration with Arizona Public Service Company (APS). Data for assembly of *tracker and total system* are excluded since its contribution is assumed to be small.

Values for **production of III-V semiconductor cells** are taken from the production processes of system 3. These include energy consumption during process or production of germanium wafer, metal-organic vapor phase epitaxy, use of cleanroom, photolithography, metals for evaporation and overall consumptions during cell technology production (Peharz & Dimroth 2004).

### **3.4 Cradle-to-gate results – system 1 and 2**

The process inventory data are used in the following analyses of PER for system 1 and 2.

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<sup>9</sup> The values have been compared with values used for zinc steel, 29MJ/kg (Peharz & Dimroth 2004)

Table 3 show the process PER per watt peak for each system. High and low data refer to upper and lower limits of inventory data for the same process. The maximum range between the two systems is shown in bold.

**Table 3.** General parts and processes in terms of primary process energy requirements per watt peak (MJ/Wp). No differences between high and low data for lens, foundation and transformer due to a single inventory source.

General parts and processes (MJ/Wp)	System alternative 1		System alternative 2	
	High data	Low data	High data	Low data
Lens	2.5	2.5	2.3	2.3
Cell	0.2	0.2	1.3	0.9
Heat sink	1.3	1.1	3.0	2.5
Encapsulation	7.1	2.1	2.9	0.9
Tracker	13.9	4.2	7.8	2.5
Foundation	0.2	0.2	0.3	0.3
Inverter	0.7	0.3	0.7	0.3
Transformer	0.4	0.4	0.4	0.4
Assembly	0.002	0.001	0.06	0.024
Total primary process energy *	<b>26.3</b>	10.9	18.8	<b>10.2</b>

\* values may differ due to rounding

The values are calculated with 16 per cent system (AC) efficiency for system 1 and 17 per cent system (AC) efficiency for system 2. Efficiencies correspond to information given from system producers. Field performance efficiency is lower due to high wind and dust on lenses.

### 3.4.1 Development/Improvement uncertainty

Certain parameters and process data are possibly changed due to increased knowledge and optimization. In this subsection cradle-to-gate result is given for system 1 and 2, when the monocrystalline silicon cells are changed to III-V multijunction cells and when the system (AC) efficiency and amount of tracker material is varied.

When shifting cell from monocrystalline silicon to III-V multijunctions, small system design changes are necessary (Hayden 2005).

To reach high concentration level in system 2, lens material for a secondary lens is added. The amount material is estimated at NREL test facility in Golden, Colorado. With a higher concentration a cell area reduction is possible. Since the concentration in system 1 is doubled, the cell area is reduced to half. For system 2 the concentration ratio is increased sixteen times, thus the cell area is divided by 16.

**Table 4.** General parts and processes in terms of primary process energy requirements per watt peak (MJ/Wp). The amount of lens material in system 2, cells and cell area in each system are different from original configuration. There is no difference between high and low data for lens, cell III-V, foundation and transformer, since only one source for inventory data is used. The system (AC) efficiency is 26 per cent.

General parts and processes (MJ/Wp)	System alternative 1		System alternative 2	
	High data	Low data	High data	Low data
Lens	1.6	1.6	2.3	2.3
Cell III-V	1.7	1.7	1.3	1.3
Heat sink	0.8	0.7	2.0	1.6
Encapsulation	7.1	1.3	1.9	0.6
Tracker	8.6	2.6	5.1	1.7
Foundation	0.1	0.1	0.2	0.2
Inverter	0.4	0.2	0.5	0.2
Transformer	0.2	0.2	0.2	0.2
Assembly	0.0013	0.0005	0.0013	0.0005
<b>Total primary process energy *</b>	<b>20.6</b>	<b>8.4</b>	<b>13.3</b>	<b>8.0</b>

\* values may differ due to rounding

Table 4 shows general parts and processes in terms of PER per watt peak (MJ/Wp). Production of III-V multijunction solar cells needs 34 times more energy during production than the lowest production value for production of monocrystalline cells. Even with a reduction of cell area the PER for III-V multijunction cells is ten times higher than for the monocrystalline cells in system 1. Nevertheless, with smaller amount of cell material and higher efficiency, the system PER per watt peak is less. The values in Table 4 are calculated with a system (AC) efficiency of 26 per cent, for both systems.

Since system efficiency is uncertain the (AC) efficiency is varied between 14 and 30 per cent in Table 5. As a consequence PER is decreased to about 7 MJ/Wp, with 30 per cent efficiency and low energy data values. With 14 per cent efficiency PER is increased to between 25 and 32 MJ/Wp with high energy data values.

**Table 5.** Total PER per watt peak with different system (AC) efficiencies. The systems have III-V multijunction cells.

Total PER (MJ/Wp) at different system (AC) efficiency	System alternative 1		System alternative 2	
	High data	Low data	High data	Low data
14%	32.1	15.6	24.8	14.9
18%	26.6	12.1	19.3	11.6
22%	23.0	9.9	15.8	9.5
26%	20.6	8.4	13.3	8.0
30%	18.8	7.3	11.6	7.0

In general, tracker, encapsulation and lenses contribute most to the overall energy performance. Tracker production is the manufacturing process that influences the result most, except for in System 2 with low inventory data, where lenses have the greatest influence. Depending on system and inventory data, trackers contribute with 21 to 42 per cent of the total PER. With small amounts of material added to tracker and foundation, System 1 is able to support a 7- or even 10-MegaModule large module (Fletcher 2005). The smaller System 2, with two modules on one tracker, can be combined in larger systems with up to 72 modules in one row (O'Neill 2002). The added amount of steel, compared to a two module tracker, is

significant but the overall material used per module is less.<sup>10</sup> If only 70 per cent of the tracker material in Table 4 is used, the total PER is reduced from 20.6-8.4 to 18.0-7.6 in system 1. This is a reduction to 87 and 90 per cent, respectively, of the former values. For System 2, the same reduction of tracker material reduces the total PER from 13.3-8.0 to 11.9-7.6. This is a reduction to 89 and 95 per cent, respectively, of the former values.

### **3.4.2 Electricity consumption during use**

The electricity consumption during usage may be of importance for some systems. System 1 has the largest motor, i.e. a two horse powered, that runs for 20 minutes per day. Even with a lifetime of 25 years this contribution to total PER is small, i.e. between 3 and 8 per cent.

### **3.4.3 Transportation to use**

The weight of system 1 and 2 are 0.829 kg/Wp and 0.825 kg/Wp, respectively. The energy requirement for semi-trailer truck transportation is 0.72 MJ/ tonnes km (Baumann & Tillman 2004). The freight distance is about the same for both systems, namely 1680 km for a 1 MJ/Wp contribution to the total primary energy result from transportation. The transport of the systems is significant for longer freight distances from manufactory to customer. Still the distance to customer has to be doubled to contribute more than the tracker, even with the lowest inventory data for System 2.

## **3.5 CPV results**

To provide CPV technology potential, in terms of energy performance, results are based on the improvements given in section 3.4.1. Assessments done in this subsection are related to energy production at different locations. Solar irradiation differences and system losses are considered for all three systems. The result is presented as energy return factors (ERF), see equation 4 in section 2.2.

Different locations have different amount of solar irradiation or even more important, different amount of direct light. Field performance efficiency of system 1 has been calculated to be 12.5 per cent, with all losses included. For system 2, no information of field performance has been given and the theoretical value for system efficiency, 16 per cent, is used. The result is based on modified systems where the monocrystalline cells are replaced by III-V multijunction cells. The state-of-the-art cell efficiency of 38 per cent (Yamaguchi 2004) has been used. The system (AC) efficiency of 29.5 per cent is calculated by including 23 per cent system losses to the cell efficiency<sup>11</sup>. All parts of the systems are assumed to have equal life times of 25 years, except for movable parts as motor and actuators with a normal life time between ten and fifteen years. Nevertheless, their contribution to the overall result is insignificant. Inverters and transformers with a life time of about fifteen years influence total PER more, but their lifetimes are extended to 25 years since smaller parts are assumed to be replaceable (Fletcher 2005).

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<sup>10</sup> Assumption based of comparison with similar, one axis, trackers used for flat plate solar cells.

<sup>11</sup> Based on losses calculated for design alternative 1 where the cell efficiency is calculated to be 16.2 and actual field efficiency is 12.4, i.e. 23 per cent less.

**Table 6.** Energy return factor (ERF) for the three studied systems at different system efficiency, locations and solar irradiations. A life time of 25 years is assumed for all systems. The solar irradiation values are valid for two axis trackers. Max and min values are given in bold. In the gray reference field, ERF is given for present systems with monocrystalline silicon cells (field efficiency 12.5%).

Solar irradiation	Germany 1000 kWh/(m2 yr)			Spain 1900 kWh/(m2 yr)			Arizona 2480 kWh/(m2 yr)		
System	1	2	3	1	2	3	1	2	3
<b>ERF, 12.5% efficiency</b>	<b>6.5-14.6</b>	<b>5.8-8.2</b>	<i>n.a.</i>	<b>12.4-27.8</b>	<b>11.0-15.6</b>	<i>n.a.</i>	<b>16.2-36.3</b>	<b>14.3-20.3</b>	<i>n.a.</i>
ERF, 26% efficiency	13.9-31.7	26.4-60.2	<b>13.5-18.3</b>	26.4-60.2	26.0-34.2	25.7-34.7	34.5-78.6	33.9-44.6	27.6-37.4
ERF, 29.5% efficiency	15.1-36.0	15.5-20.4	15.3-20.7	28.7-68.3	29.5-38.8	29.1-39.4	37.5 - <b>89.2</b>	38.5-50.6	31.3-42.4

*n.a.* not available

In comparison to current CPV systems ERF is significantly increased. However, in Table 6 a large uncertainty due to location and inventory data are shown. ERF ranges from 13.5 to 89.2 for the assumed future systems. This can also be compared to present flat plate polycrystalline silicon cells that have an ERF of 6.7 with 9.8 per cent (AC) efficiency. Calculation is performed with a life time of 25 years in Arizona solar conditions<sup>12</sup>.

The area requirements for a net production of 1 MWh electricity with ground-mounted p-Si are about 0.3 m<sup>2</sup>. This is calculated with a life time of 25 years and a solar irradiation of 1970 kWh/m<sup>2</sup> yr<sup>13</sup>. The three analyzed CPV systems require 0.06 to 0.16 m<sup>2</sup>/MWh, under similar conditions, see Table 7<sup>14</sup>.

**Table 7.** Required area per MWh electricity. Assuming a 25 years of life time and solar irradiation valid for a two-axis tracker in Spanish conditions, i.e. 1900 kWh/(m2 yr).

Required area (m2) per MWh electricity	System 1		System 2		System 3	
	High	Low	High	Low	High	Low
Area at efficiency 26%	0.07	0.08	0.11	0.15	0.11	0.16
Area at efficiency 29.5%	0.06	0.07	0.10	0.13	0.07	0.10

The values in Table 7 are calculated with a required system area equal to the aperture area. If shadowing from the erected system is considered, the area requirement could be several times higher. This is important to notice when several systems are supposed to be mounted at the same place.

<sup>12</sup> Calculated for solar irradiation at 1970 kWh/m<sup>2</sup>\*yr when cell leaning 15 degrees from vertical level and have a south direction. Primary process energy includes module material and balance of system and is 5900 MJ/m<sup>2</sup> (Alsema & Nieuwlaar 2000).

<sup>13</sup> Calculated for horizontal solar irradiation of 1700 kWh/m<sup>2</sup> yr (European average) that when cell is leaning 15 degrees from vertical level and have a south direction gives 1970 kWh/m<sup>2</sup> yr.

<sup>14</sup> Due to lack of statistics of European solar irradiation valid for two-axis tracking concentrators, approximation has been done with the aid of NREL solar irradiation database (NREL Solar Maps 2006). Furthermore, result is based on losses calculated for System 1 with cell efficiency 16.2 and actual field efficiency 12.4, i.e. 23 per cent less.

## 4 Polymer photovoltaics

A general overview of the technology of PPV is given followed by a description of the specific materials and processes that is likely to be used for manufacturing. Subsequently, inventory data are presented with respect to uncertainties in process data, design choice and possible improvements. The cradle-to-gate results are complimented by sensitivity analysis on assumptions done in calculations and a discussion of how transportation to consumer influences the results. Finally, the results are formulated as energy return factors (ERFs) in relation to lifetime, efficiency and solar irradiation, followed by the area requirements for PPV electricity generation.

### 4.1 General structure

PPVs are thin film photovoltaic devices that use polymers to absorb the energy in light and convert it to electricity. Development of organic PV devices started with research on organic dyes showing photoelectric properties in the 1950s. The idea of copying Nature's way to generate electricity was tantalizing and the main investigated dye was chlorophyll. Studies on the photoelectric properties of polymers began thirty years later in the 1980s (Spanggaard and Krebs 2004). Today, research is being performed on a broad range of organic PVs, but most effort is still put on development of the active material and not on the process of producing them. However, the high potential of low cost processing of these solvable materials and co-evolution with kindred technologies as organic light emitting devices and organic field effect transistors, have lead to a growing industrial interest.<sup>15</sup> This is believed to accelerate development enough to put organic PV's in niche markets within one or two years (Brabec 2004).

PPV is the type of organic PV that is studied in this report. To distinguish PPV as one separate organic PV technology, a closer look at the cell materials is necessary. Experiments are done on a number of double combinations of organic active materials, i.e. dye/dye, dye/polymer, polymer/polymer, polymer/fullerene and polymer/metal-oxide. Here one material acts as charge donor and the other as charge acceptor. The first two double combinations use a photosensitive dye as electron donor. By absorption of a photon the electron is released (dissociated) from the dye into a conducting material, where it travels to the cathode. At the same time as an electron is released, a hole is created.<sup>16</sup> The hole is lead through an electrolyte (a hole conducting material) to the anode.

In the case of polymer/polymer and polymer/fullerene active materials a polymer has replaced both the dye, as electron donor, and the electrolyte, for hole transportation. The (electron) conducting material is replaced by either another polymer or a fullerene compound.<sup>17</sup> Photovoltaics with this type of active material are defined as PPV in this study.

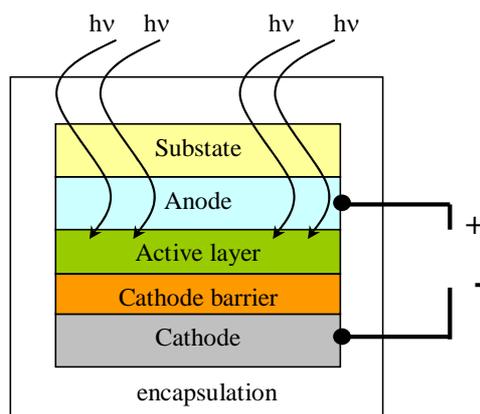
The general configuration of a PPV device is a transparent substrate, an anode, an active layer a cathode barrier and a cathode. Sometimes an additional layer, not seen in Figure 14, between the anode and the active layer is deposited.

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<sup>15</sup> See e.g. Halls and Wilson (2004) and Wormser and Gaudiana (2003).

<sup>16</sup> Holes are positive charge carriers and are the positive counterpart to electrons.

<sup>17</sup> In recent published articles (Tuladhar et al. 2005) it is shown that fullerenes acts as both negative (electron) and positive (hole) charge acceptor and thus conducts both electrons and holes.



**Figure 14.** Configuration of a PPV device. Photons ( $h\nu$ ) are absorbed in the active layer of the cell and charges travel towards respective pole, electrons to the cathode and holes to the anode.

## 4.2 Specific processes and materials

Manufacturing process alternatives and materials (type and thickness) in the general PPV structure, considered in this report, are described here. Improvements on these are discussed in a separate heading at the end of this section. The flowchart in Figure 15 outlines the processes explained under following headlines.

**Table 8.** A compilation of material choices and thicknesses considered in calculations.

Material intensity/ Layer thicknesses	material(s)	low	high unit	deposition method
Cathode	Al	50	200 nm	Vacuum evaporation
Cathode barrier layer	C60	100	500 nm	Vacuum evaporation
Cathode barrier layer	LiF	1	4 nm	Vacuum evaporation
Active layer	BHJ, Polymer/Fullerene	200	400 nm	Printing
Anode barrier layer	PEDOT:PSS	1	2 $\mu\text{m}$	Printing
Anode	ITO	60	150 nm	Sputtering
Anode	PEDOT VPP	30	100 nm	Vapor phase polymerization
Substrate	Glass	100	250 $\mu\text{m}$	-
Substrate (PET/Al <sub>2</sub> O <sub>3</sub> )	PET/Al <sub>2</sub> O <sub>3</sub> barrier	1	2 layers	Lamination
Substrate (PET/Al <sub>2</sub> O <sub>3</sub> )	PET	12	75 $\mu\text{m}$	
Substrate (PET/Al <sub>2</sub> O <sub>3</sub> )	Al <sub>2</sub> O <sub>3</sub>	10	60 nm	Sputtering
Encapsulation material, back	Glass	100	250 $\mu\text{m}$	Lamination
Encapsulation material, back (Steel/PET)	Steel	80	180 $\mu\text{m}$	Cold pressed
Encapsulation material, back (Steel/PET)	PET	75	23 $\mu\text{m}$	Lamination

### 4.2.1 Substrate and encapsulation

PPVs have the attractive feature of potential low cost production through roll-to-roll processing. This would require highly flexible substrates and encapsulation materials (Kroon et al. 2005). Due to degradation of the active layer and oxidation of the cathode, the critical aspects for device lifetime are encapsulation and substrate permeability to oxygen and water. Ordinary polyethylene terephthalate (PET) plastics have the required flexibility but are highly permeable to such substances. Commercially organic display technologies have compensated flexibility with lifetime by using rigid glass.<sup>18</sup> However, if the glass materials are of high quality and very thin (100 $\mu\text{m}$  to 250 $\mu\text{m}$ ) it is believed that glass can be used as front encapsulate/substrate in future flexible PPVs in a roll-to-roll process. Back encapsulation material could then be a PET covered thin, about 130 $\mu\text{m}$ , steel sheet (Krebs 2005). The PET film (23-70 $\mu\text{m}$ ) and the steel sheet are assumed to be laminated together.

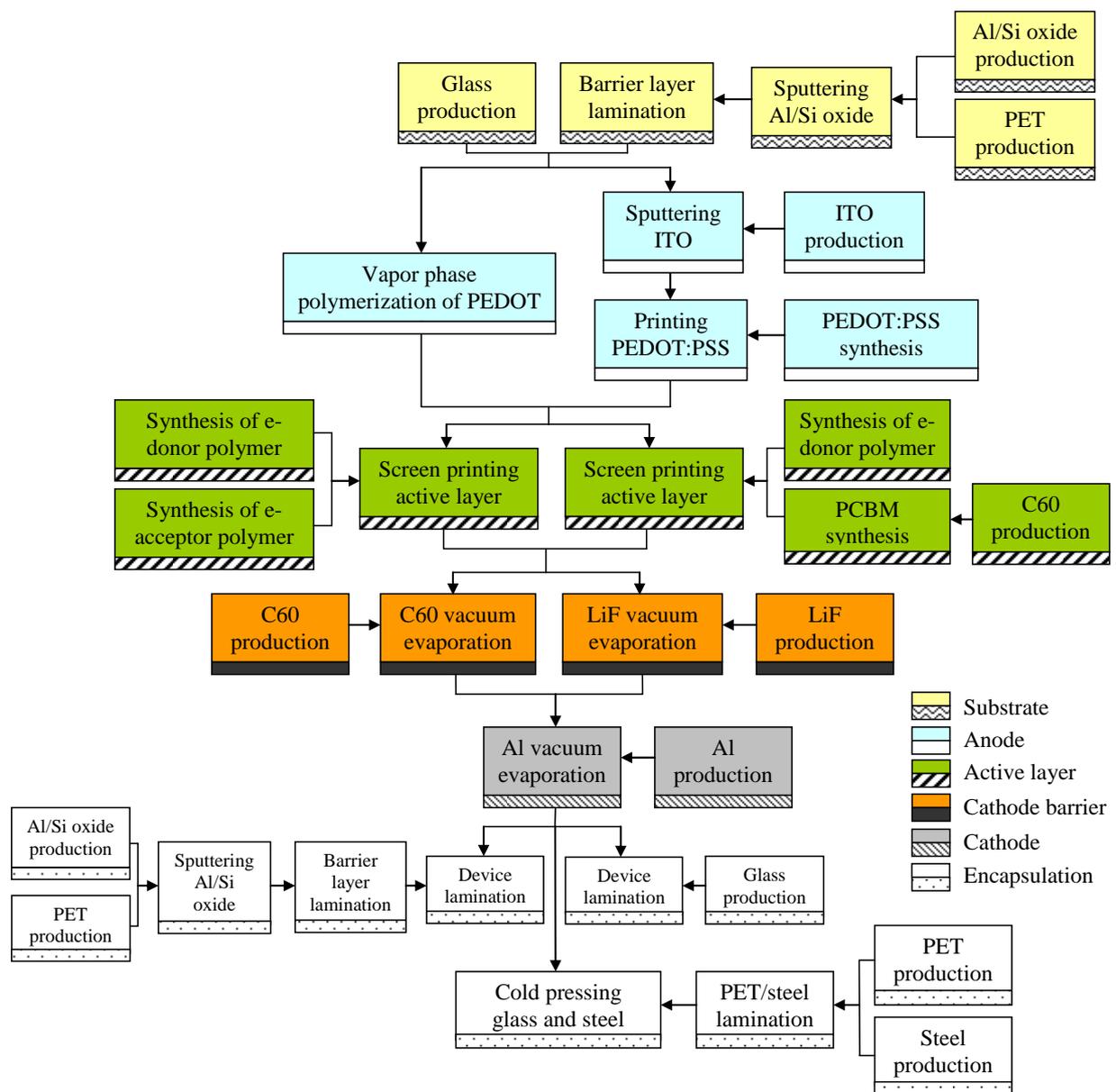
<sup>18</sup> See e.g. Siemens 2003.

A number of non-glass barrier films are presently used to encapsulate i.e. food, medicine and electronics and materials engineered specifically to flexible OLED purpose have been developed (Burrows et al. 2001).<sup>19</sup> Such barrier films consist of multiple layers, where at least one layer is silicon or aluminum oxides ( $\text{SiO}_x$  or  $\text{Al}_2\text{O}_3$ ) and the others are polymer materials such as PET. These oxides are impermeable to oxygen and water, but defects after deposition make this property go down. A thicker layer is generally better, even though a too thick layer will crack when the device is bended (Gruniger & Rudolf von Rohr 2004). Barrier films used in this report have  $\text{Al}_2\text{O}_3$  sputtered on the polymer to a thickness of between 10nm to 60nm. Polymer film thickness varies from  $12\mu\text{m}$  to  $75\mu\text{m}$ .<sup>20</sup> When two layers are deposited they are assumed to be laminated together.

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<sup>19</sup> See e.g. TOPPAN 2005 and Mitsubishi 2005.

<sup>20</sup> For research examples on thicknesses and processing see: Bieder et al. 2005, Charton et al. 2005 and Hedenqvist & Johansson 2003.



**Figure 15. PPV production flowchart.** Each box represents one process. Different design choices are represented by vertical flows, e.g. the anode can be either glass or (flexible) barrier layer followed by either vapor phase polymerized PEDOT or sputtered ITO and printing. All combinations are possible but cold pressed encapsulation, which can only be combined with a glass substrate.

Flexible substrates used in laboratory tests are commonly ITO (indium doped ten oxide) covered PET, where the ITO layer primary serves as anode.<sup>21</sup> But since the water content of the PET substrate alone is enough to destroy the device, ITO additionally functions as an internal water barrier (Charton et al. 2005). If the ITO-anode is replaced by another material, with higher permeability, a barrier layer such as  $\text{SiO}_x$  or  $\text{Al}_2\text{O}_3$  is used.

<sup>21</sup> See e.g. Al-Ibrahim et al. 2004

Calculations are based on lamination of the possible combinations: glass/glass, barrier film/glass and barrier film/barrier film or cold pressed glass/steel.

#### 4.2.2 Anode

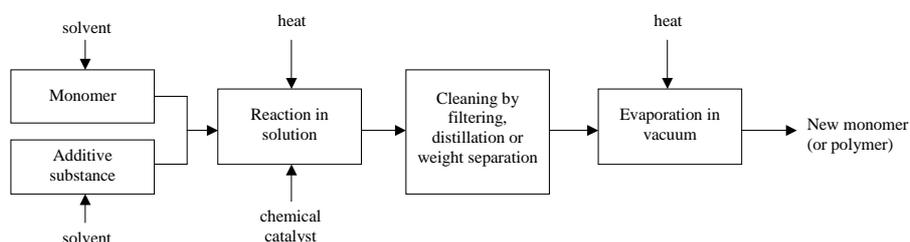
ITO is used as anode material in the majority of PPV laboratory devices and commercially OLEDs. However, ITO has unfavorable economic characteristics, it is therefore probable that ITO is replaced when PPV is commercialized (Shaheen 2005). The alternative is a conductive polymer PEDOT which can be deposited on the substrate at the same time as it is synthesized (Admassie et al. 2006 and Winther-Jensen & Krebs 2006). In general, conductivity increases with PEDOT thickness while light permeability decreases. Admassie et al. (2006) had a PEDOT thickness of 60nm in their experiments. In this analysis thickness is varied from 30nm to 100nm.

If ITO is used as anode it is sputtered on the substrate to a thickness of between 60nm and 150nm. An additional layer is deposited to impede chemical reaction between ITO and the active layer. This layer is a PEDOT and PSS mixture that can be printed on the ITO layer to a thickness of 1 $\mu$ m to 2 $\mu$ m (Risø National Laboratory 2005).<sup>22</sup> The state-of-the-art device has a PEDOT:PSS thickness of 25 nm (Li et al. 2005). This thin layer is deposited by spin coating and not by printing. The lower limit for a screen printed layer is 1 $\mu$ m with today's technology (Stema 2005) hence a 25 nm layer is not considered in calculations.

#### 4.2.3 Active layer

The active material consists of a blend of two polymers or one polymer and one fullerene compound. Conducting polymers are called conjugated. Since they are possible to chemically tailor the exact polymer used in the PPVs are not of interest for this study.<sup>23</sup> Instead the lab-scale synthesis is generalized to fit most conjugated polymers.

The iterative procedure starts with a dissolved monomer, see Figure 16. The solution is mixed with an additional substance to react with the monomer. For the reaction to take place different substances or/and heat is added to the mixture. After a period of time, how long depending on type of reaction, the solution is cleaned through filtering, distillation or weight separation. Finally the sample is evaporated in vacuum to produce another monomer or, if it is the last step of the synthesis, the final polymer.



**Figure 16.** The iterative synthesis procedure of conjugated polymers.

For simpler conjugated polymers this procedure is repeated two or three times with different additives, catalysts and cleaning methods. More complex polymers can require as many as fifteen steps. Most common solvents used are toluene, chloroform and dimethylformamid

<sup>22</sup> PEDOT:PSS is an abbreviation for Poly3,4-ethylenedioxythiophened:Polystyrenesulfonate

<sup>23</sup> However, the most common polymers used as electron donors are MDMO-PPV (poly(2-methoxy-5-(3',7'-dimethyloxy)-1,4-phenylene-vinylene)) and P3HT (poly(3-hexylthiophene)).

(DMF).<sup>24</sup> At lab, heat for catalyzing and evaporation is generally delivered by a hot plate fired by electricity. Vacuum is achieved by a vacuum pump.

Fullerenes are the common name for ball-shaped carbon molecules. The simplest one is C<sub>60</sub> and consists of 60 carbon atoms bounded together to form a soccer ball sphere. Fullerenes were first produced by the carbon arc method, where individual graphite rods are vaporized with electrical currents in low-pressure inert gas (Krätschmer et al. 1990). More commonly used today are combustion methods with a continuous low flow of hydrocarbon fuel that are burned at low pressure to produce soot containing fullerenes (Hebgen et al. 2005). The weight yield of C<sub>60</sub> in the soot is about 0.5 per cent of the burned hydrocarbon toluene (Takehara et al. 2005 and Campbell 2005) at an industrial scale. Subsequent cleaning and purification can separate more than 90 per cent of the produced C<sub>60</sub> (Komatsu et al. 2004). Other production techniques involving high energy by concentrated sunlight have been described (Flamant et al. 2004) and can be considered for further development.

Fullerenes alone are not solvable and can therefore not be printed if they do not have an organic side chain. A common C<sub>60</sub> molecule with this side chain used in the active layer is PCBM<sup>25</sup>. The synthesis of PCBM from C<sub>60</sub> consists of three steps where each step can be assumed to require the same amount of energy as synthesis of a conjugated polymer (Perzon 2005 and Hummelen et al. 1995). The PCBM content in the active layer is 50 to 80 per cent, but in calculations it is set to 60 per cent.

The ability to print the photo active layer has been one of the most interesting features of PPVs. It has been announced that any printing technology can be used, i.e. ink-jet, screen, offset or flexo (Brabec 2004), but to the authors' best knowledge only examples of ink-jet and screen have been published (Shah & Wallace 2004 and Shaheen et al. 2001). The critical parameter for printing text and images is resolution and thus printing technology has been optimized regarding that. For printing the PPV active layer the crucial parameter is instead printed thickness and uniformity over a large area. These requirements are well suited for screen printing, which is the printing technology considered in this report.

The optimal thickness of the bulk heterojunction is a few hundred nanometers (Sariciftci 2004 and Li et al. 2005), but these thin films are difficult to produce with current industrial screen printing methods without defects. These defects influence cell performance negatively and can be reduced in two ways. Either printing is done more carefully with better performance of the printing technology or the printed layer is increased to about 1 μm. This thicker layer could possibly be reduced to 250-500 nm by post processing methods (Krebs 2005). The printed layer is assumed to be 200-400 nm in calculations.

#### **4.2.4 Cathode and cathode barrier layer**

Of all possible cathode materials aluminum is both the most common in laboratory experiments and the most probable alternative for commercial PPV devices (Krebs 2005). The aluminum cathode thickness varies in experiments and this study considers thicknesses between 50 to 200 nm.

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<sup>24</sup> Production of solvents is not considered in calculations.

<sup>25</sup> PCBM is an abbreviation for: [6,6]-phenyl-C61-butiric acidmethyl ester.

OLEDs seem to have better performance if a very thin layer LiF is deposited between the cathode and the active layer.<sup>26</sup> The exact function of this layer is not found for PPVs. However, since non-oxidized aluminum is very reactive an isolating layer of C<sub>60</sub> can be used to impede chemical reaction (Krebs 2005). This layer is then deposited instead of LiF to a thickness of 50-200 nm. Both aluminum, LiF and C<sub>60</sub> is vacuum evaporated.

#### **4.2.5 Possible improvements**

Following processes are considered for further improvements in section 4.4.1, either since they are regarded as young with large potential for further development or due to their energy intensive nature.

Encapsulation materials with low permeability to oxygen and water are already an intense field of research and development is probable in terms of function. The barrier layers in these materials are assumed to be sputtered. Since sputtering is very energy intensive it is likely that this method is replaced in the future.

Evaporation of aluminum is the common laboratory deposition method for thin aluminum layers. However, other techniques as e.g. printing are possible (Zhang 2005).

Fullerenes were discovered only 20 years ago and production and purification processes have undergone a significant development from carbon arc method to high yield combustion methods. Further development from the assumptions done in this report is probable. C<sub>60</sub> yield could increase and energy requirements should go down while operations optimize due to learning and increased demand.

Laboratory state-of-the-art cell efficiency is presently close to 5 per cent (Reyes-Reyes et al. 2005 and Li 2005), while the cradle-to-gate results are presented for a device efficiency of 1 per cent. The difference between the PPV devices, put forward in this report, and current state-of-the-art is e.g. optimization in the state-of-the-art devices through laboratory deposition methods, which are not suitable for large scale manufacturing. Furthermore, no device losses are considered. However, the promising 5 per cent cells demonstrate a potential for performance improvement.

#### **4.3 Process inventory data**

When data sources, calculations and estimations are presented, process data of production of aluminum and steel are similar for PPV and CPV, hence they are not presented again.<sup>27</sup> All data used in calculations are given in Table 9.

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<sup>26</sup> LiF is an abbreviation for Lithium Fluoride.

<sup>27</sup> One exception is float glass, where data are used in a different way for PPV than for CPV.

**Table 9.** A compilation of process inventory data. Energy requirements are given as MJ primary energy.

Process	low data unit	electricity	reference	high data unit	electricity	reference
VPP PEDOT	17,2 MJ / m <sup>2</sup>	100%	estimated	34,8 MJ/m <sup>2</sup>	100%	estimated
Glass production	* MJ/kg	n.a.	ETH-ESU 1996	39,8 MJ/kg	n.a.	estimated, 3x low
PEDOT:PSS synthesis	45,8 MJ/kg	23%	estimated	2008 MJ/kg	100%	estimated
Polymer synthesis	45,8 MJ/kg	23%	estimated	2009 MJ/kg	100%	estimated
PCBM synthesis	4154 MJ/kg	93%	estimated	6366 MJ/kg	92%	estimated
Al production 50.50	* MJ/kg	n.a.	BUWAL 250	81,4 MJ/kg	75%	Sunér 1996
Steel production (low recycling)	11,0 MJ/kg	29%	Sunér 1996	* MJ/kg	n.a.	ETH-ESU 1996
PET production	45,8 MJ/kg	23%	PlasticsEurope			
C60 production	4108 MJ/kg C60	94%	estimated	4357 MJ/kg C60	89%	estimated
Lamination	* MJ/m <sup>2</sup>	77%	BUWAL 250	* MJ/m <sup>2</sup>	100%	BUWAL 250
Printing	0,09 MJ/m <sup>2</sup>	100%	estimated	0,51 MJ/m <sup>2</sup>	100%	estimated
Barrier material production	2,80 MJ/m <sup>2</sup>	n.a.	estimated	71,0 MJ/m <sup>2</sup>	n.a.	estimated
Sputtering	0,21 MJ/m <sup>2</sup> /nm	100%	estimated	0,51 MJ/m <sup>2</sup> /nm	100%	estimated
Vacuum evaporation	0,08 MJ/m <sup>2</sup> /nm	100%	estimated	0,17 MJ/m <sup>2</sup> /nm	100%	estimated

n.a. not available  
\* not an open source

Data for *production of PET film* is gathered from PlasticsEurope (2005). They present inventory data as packed PET film divided in fuel production and delivery, energy content of delivered fuel, energy use in transport and feedstock energy. Energy content of delivered fuel and energy use in transport are used and 23 per cent of this energy origin from electricity. No other data source is found on PET film.

Energy for *production of float glass* is used as an estimation for the relatively higher quality Pyrex glass used as encapsulation or/and substrate. This is probably a low estimation and thus a higher value is estimated to be three times the value for float glass. No information is found on the electricity share. Data is collected from ETH-ESU 1996.

Since no data are found on *production of ITO*, this process is considered later, in section 4.4.2.

Data for *synthesis of active layer polymers* is collected from two sources. Laboratory scale data is collected at Chalmers division of polymer technology (Perzon 2005). Calculations are performed for three iterative synthesizing steps.<sup>28</sup> The lower limit data is estimated to be the same as the energy for industrial production of PET plastics, i.e. about 25 times less than the higher limit. Same assumptions are done for synthesis of PEDOT and PSS, see appendix section 8.1. 23 and 100 per cent origin from electricity in lower and higher limits respectively.

Energy requiring processes during *vapor phase polymerization of PEDOT* is printing a catalyst, drying and heating done under moderate temperatures for short time (Krebs 2006). High and low values stem from screen printing and from assumptions for process scaling. 100 per cent of the energy comes from electricity, see appendix section 8.2.

Primary energy needed to produce *fullerene C<sub>60</sub>* is calculated in consultation with Eleanor Campbell at Göteborg University.<sup>29</sup> Synthesis of the solvable derivate PCBM includes three steps (Hummelen et al. 1995) that are assumed to require the same energy as synthesis of conjugated polymers. For calculation and assumptions on C60 and PCBM, see appendix section 8.3 and 8.4. High and low values are given by high and low estimations during calculations.

*Plastic encapsulates with barrier layers* are assumed to be a sputtered layer of aluminum oxide enclosed by PET film. Number of layers, i.e. 1 or 2, thicknesses and energy requirement

<sup>28</sup> This iterative procedure is described further in 4.2.3 *Active layer*.

<sup>29</sup> References used for the calculation are Takehara et al. (2005) and Komatsu et al. (2004).

for sputtering gives the high and low values for this process. Calculations and corresponding references are found in appendix section 8.6.

**Production of LiF** is assumed to be negligible since the layer used is only a few nanometers. Thus, energy consumption during this production needs to be 100 to 1000 times more than for other layers to affect results.

Large scale **sputtering ITO and barrier oxides** are estimated in consultation with Henrik Fredriksen, research engineer at Department of Microtechnology and Nanoscience, Chalmers. Calculation is done on a large laboratory sputter and on assumptions for an industrial in-line sputter. High and low values are given by a range in data estimations for the industrial process. See section 8.5 for further information on calculations.

Energy requirements for **industrialized screen printing** are taken from Stema printing company in Borås, Sweden, and in consultation with Ingmar Kjellstedt (Stema 2005). Information of the special procedure of screen printing solar cell active material are received from Frederik Krebs at the Danish Polymer Centre, Risø, Denmark. High and low estimations origin from different estimates of consumed process energy and number of printed layers. Calculations are found in appendix section 8.7.

Energy requirements for **vacuum evaporation of C60 and aluminum** cathode are calculated from Risø Laboratory vacuum evaporator. Energy for e-beam and thermal evaporation is given as high and low values respectively. For calculation see section 8.8.

**Lamination** data are taken from BUWAL 250, where the high value corresponds to lamination of aluminum on paper and the low value to lamination of a plastic foil on paper.

#### **4.4 Cradle-to-gate results**

Cradle-to-gate results are given as system PER per watt peak and for each general part of the technology. Since watt peak is defined in relation to device area, it is assumed that the PPV cells cover 90 per cent of this area. Hence, with a cell efficiency of 10 per cent the device efficiency is 9 per cent.

In Table 10 results are presented in relation to the flowchart in Figure 15. For the columns “Design alternative left” the far left alternative in the flowchart is chosen, where several vertical flows are presented. For the columns “Design alternative right” the right alternative is chosen. The encapsulation process alternative with cold pressed glass and steel is represented in the columns “Design alternative: pressing”. This design option can be combined with any anode, active layer, cathode barrier layer and cathode, but must have a glass substrate (Design alternative left)<sup>30</sup>.

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<sup>30</sup> The uncertainties in Table 10 can not be seen as statistical uncertainties, thus average values will not be calculated.

**Table 10.** General parts and processes in terms of primary energy requirements per watt peak (MJ/Wp). Values are calculated with a cell efficiency of 1 per cent and watt peak (Wp) defined as output power under 1000 watts per m<sup>2</sup> solar irradiation. Processes lowest and highest energy input are presented in bold figures. All design alternative combinations are possible but cold pressed encapsulation, which has to be combined with a glass substrate.

General parts and processes (MJ/Wp)	Design alternative: left				Design alternative: right				Design alternative: pressing				Total	
	Low material intensity		High material intensity		Low material intensity		High material intensity		Low material intensity		High material intensity		min	max
	Low data	High data	Low data	High data	Low data	High data	Low data	High data	Low data	High data	Low data	High data		
Substrate	0.37	1.11	0.92	2.76	<b>0.33</b>	0.70	3.79	<b>7.94</b>	only design alternative: left				0.33	7.94
Anode	1.91	3.87	1.91	3.87	<b>1.38</b>	3.71	3.44	<b>9.13</b>	any				1.38	9.13
Active layer	<b>0.11</b>	0.22	0.20	<b>0.39</b>	<b>0.12</b>	0.20	0.24	0.41	any				0.11	0.41
Cathode barrier layer	1.00	2.02	5.02	<b>10.09</b>	<b>0.01</b>	0.03	0.06	0.13	any				0.01	10.09
Al cathode	<b>0.44</b>	0.94	1.75	<b>3.77</b>	<b>0.44</b>	0.94	1.75	<b>3.77</b>	any				0.44	3.77
Encapsulation	<b>0.33</b>	0.70	3.79	<b>7.94</b>	0.39	1.15	0.94	2.81	1.30	2.58	1.89	5.76	0.33	7.94
Sum	4.2	8.9	13.6	28.8	2.7	6.7	10.2	24.2					2.6	39.3

The aggregated energy input for all possible design alternatives is between 2.6 and 39.3 MJ/Wp.

Comparing high limit data, a flexible barrier layer as substrate/encapsulation requires 2.5 times more energy than glass, while for lower limit data barrier layer and glass have similar energy requirements. An ITO anode deposited by sputtering has most energy input of all general parts, 2.4 times higher than the alternative VPP PEDOT. However, VPP PEDOT and ITO have approximately same data for low thicknesses (low material intensity values). The active layer is not influencing the result more than, at most, 10 per cent.<sup>31</sup> A 500 nm vacuum evaporated C<sub>60</sub> cathode barrier layer has major influence on the result, while the LiF layer is negligible in any case. About 90 per cent of the C<sub>60</sub> cathode barrier PER origin from vacuum evaporation, hence production of C<sub>60</sub> is only 10 per cent. The large span in C<sub>60</sub> cathode barrier layer data (Design alternative: left) is due to large uncertainty in layer thickness; 100nm to 500nm.

#### 4.4.1 Development/Improvement uncertainty

Certain parameters and process data are possibly changed due to increased knowledge and optimization. In this subsection this potential reduction in results is analyzed for deposition through sputtering and vacuum evaporation, fullerene production and device efficiency.

With a 50 per cent reduction of the sputtering energy requirements, the min result will decrease 37 per cent and the max result 30 per cent. Thus, the overall energy necessary to produce a PPV device is to a large extent dependent on this parameter. The general parts including sputtering processes are the flexible barrier substrate/encapsulation and the ITO anode.

The cathode barrier layer and the cathode itself are deposited by vacuum evaporation. This process is calculated to require 14 MJ/m<sup>2</sup> to 30 MJ/m<sup>2</sup> for a 200 nm layer. The energy for these two layers is reduced by 43 per cent to 49 per cent if the energy requirement for vacuum evaporation is reduced by half. The min and max overall results are changed by 8 per cent and 15 per cent respectively.

The C<sub>60</sub> yield in combustion of toluene is at present 0.5 per cent. The parts influenced by this factor are the cathode barrier layer and the active layer. A 10 fold increase of C<sub>60</sub> yield the cathode barrier layer energy decreases with 12 per cent and the overall min result is reduced 1 per cent and the max 2 per cent. The active layer is not considered due to its minor influence on overall results.

Table 10 is calculated with a device efficiency of 1 per cent. The energy requirement for each process and the overall result are linearly dependent on this parameter. Thus, if efficiency doubles the energy requirements will reduce by half.

#### 4.4.2 Uncertainty induced by assumptions

Processes where inventory data was not found or where data was roughly estimated is controlled by sensitivity analysis. These processes are ITO production, PSS production and glass.

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<sup>31</sup> For 10 per cent result dependency of the active layer, the lowest values are taken for all general parts but the active layer.

The layer of ITO is at most 150nm thick and thus the total amount ITO is only about  $2 \times 10^{-8} \text{ m}^3$  per watt peak with a cell efficiency of 1 per cent. ITO consists to most part of indium with a density of  $7310 \text{ kg/m}^3$  (Webelements 2005). The PER for producing ITO needs to be 8200 MJ/kg (about 2 times PER for  $\text{C}_{60}$  production) to contribute to the system PER with 1 MJ/Wp. This is about 2.5 per cent of the system max.

Assuming that PSS is blended with PEDOT in a 1:1 weight concentration, a doubling of the energy requirements for producing PSS would then influence the overall result 0.7 per cent and the anode by 3.7 per cent, at most.

The high quality glass used in calculations is assumed to require three times more PER than ordinary glass. High quality glass production needs to be about nine times more energy requiring than ordinary glass to reach the PER (high) of the alternative, flexible barrier layers.

Production of solvents and the processes of cold pressing and cutting, cleaning etc. are not considered in the results.

#### **4.4.3 Transportation to use**

With the thickest layer alternatives, but without glue from lamination the PPV device is about 0.5 mm thick. Assuming the double thickness, a density of  $1000 \text{ kg/m}^3$  and a cell efficiency of 1 per cent the weight per watt peak is 0.11 kg. The energy requirement for semi-trailer truck transportation is 0.72 MJ/ tonnes km (Baumann & Tillman 2004). The freight distance would be about 12500 km for a 1 MJ/Wp contribution to the result from transportation. This distance is more than four round trips Göteborg-Paris.<sup>32</sup>

#### **4.4.4 Balance-of-system**

It is not yet possible to define the total balance of system for PPV devices. However if it will be connected to the grid, a primary energy of about 1 MJ/Wp is added to the system from inverters and transformers. Furthermore, if the PPV devices necessitate additional encapsulation for increased weatherability the module encapsulation materials would add approximately 200 MJ per  $\text{m}^2$  and 400 MJ per  $\text{m}^2$  for an aluminum frame (Alsema & Nieuwlaar 2000). With PPV device efficiency of 1 per cent the added energy requirements increases with 67 MJ/Wp.

### **4.5 PPV results**

Due to the large uncertainty in design solutions it is not possible to single out one part of the potential PPV device that is more essential to overall PER than the others. Result is dependent of combinations of processes and layer thicknesses, see Table 10. The energy intensive process sputtering is used for both production of flexible barrier layers and deposition of ITO anode. If these design alternatives are incorporated in the PPV device the overall PER is highly dependent of the energy consumed by this process.

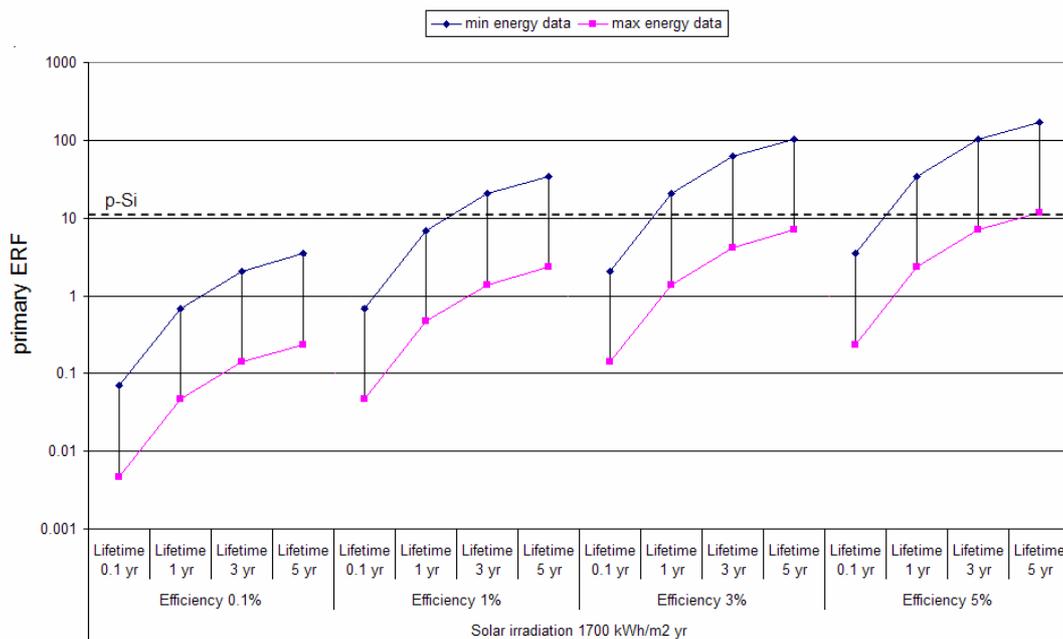
If a thick (~500nm) layer vacuum evaporated  $\text{C}_{60}$  is used, it requires at least 4 MJ/Wp with a device efficiency of 1 per cent. In a configuration with VPP PEDOT anode, glass or a thin layered barrier encapsulation this would be the most energy intensive process. However if the layer is thin (~100nm) its significance is not as apparent.

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<sup>32</sup> The distance Göteborg-Paris is 1511 km (939 miles).

To reach low energy requirement, low material intensity is generally the most important aspect, especially if sputtering or vacuum evaporation is used as deposition methods. Interesting to see is that the active layer thickness or components are almost negligible for all design alternatives, i.e. only 0.11-0.41 MJ/W<sub>p</sub>.

The device energy return factor is presented in Figure 17 in relation to device lifetime and efficiency with European average solar irradiation, 1700 kWh/m<sup>2</sup>yr. Results are presented without any balance-of-system, i.e. inverters, transformers, cables, frames or support structures. For best performance, with 5 years life and efficiency of 5 per cent, a PPV device returns 173 times the energy it consumed during manufacturing, but for worst performance, with 0.1 years life and efficiency of 0.1 per cent the return factor is only 0.005.



**Figure 17. Primary energy return factor (ERF) for PPV technology (logarithmic scale).** Device lifetime and efficiency are varied along x-axis. When ERF is larger than 1 the produced energy is larger than the primary energy requirements (PER) for producing the PV device. Low and high energy data corresponds to lower and upper limits of the cumulative uncertainties. ERF for polycrystalline silicon (p-Si) devices are 13.0. Balance-of-system is excluded for both PPV and p-Si.

The most common PV technology is presently polycrystalline silicon (p-Si) cells. Only considering the cell materials, without frame, encapsulation materials or overhead operation and equipment manufacturing, these have an ERF of 13.0 (Alsema & Nieuwlaar 2000), with a lifetime of 25 years and an efficiency of 13 per cent.<sup>33</sup>

Under average European conditions, i.e. with a solar irradiation of 1700 kWh/m<sup>2</sup>yr, the area requirement for producing 1 MWh electricity with p-Si cells is about 0.25 m<sup>2</sup>. This is calculated with an expected device life of 25 years.<sup>34</sup> To compare this with the area intensity of PPVs a compensation is done for different lifetimes, e.g. if the PPV cell has 5 years lifetime it can use the same area 5 times.

<sup>33</sup> Calculated for solar irradiation 1700 kWh/m<sup>2</sup> yr and a (module/cell) area utilization of 90 per cent. Production energy requirement of the cell materials used per m<sup>2</sup> module is 3500 MJ.

<sup>34</sup> Same assumptions are done for p-Si as above.

**Table 11.** The required area for production of 1 MWh electricity during 25 years. Solar irradiation is 1700 kWh/yr m<sup>2</sup>. Balance-of-system is not included.

Area intensity (m <sup>2</sup> /MWh electricity)		min energy data	max energy data
Efficiency 0.1%	Lifetime 0.1 yr	*	*
	Lifetime 1 yr	*	*
	Lifetime 3 yr	50.5	*
	Lifetime 5 yr	36.8	*
Efficiency 1%	Lifetime 0.1 yr	*	*
	Lifetime 1 yr	3.1	*
	Lifetime 3 yr	2.7	9.3
	Lifetime 5 yr	2.7	4.6
Efficiency 3%	Lifetime 0.1 yr	1.7	*
	Lifetime 1 yr	0.9	3.1
	Lifetime 3 yr	0.9	1.1
	Lifetime 5 yr	0.9	1.0
Efficiency 5%	Lifetime 0.1 yr	0.7	*
	Lifetime 1 yr	0.5	0.9
	Lifetime 3 yr	0.5	0.6
	Lifetime 5 yr	0.5	0.6

\* no net production

From PPV device efficiencies 1 per cent to 5 per cent, the area intensity is 2 to 15 times the p-Si area intensity. For some cases, with low efficiency and lifetime, PPV has no net electricity production.

## 5 Conclusions

The economic advantages of the two analyzed technologies are for PPV; device materials with expected roll-to-roll manufacturing procedure, and for CPV; very small cell area requirements. Thus, there exists an obvious potential for cost reduction, even though these advantages over p-Si are, to the authors' knowledge, not fully analyzed. In this study the potential improvement in energy performance have been calculated and compared to the flat plate p-Si PV technology. The p-Si system boundaries have been adjusted to agree with PPV and CPV systems. Any comparison between CPV and PPV has so far been avoided, due to different system requirements and areas of application. CPVs have trackers, are connected to the grid and are suitable for centralized electricity generation as close to the Earth's equator as possible, while PPV applications are not fully developed. However, it is not probable that PPVs will be used for centralized power plant purposes, unless power efficiencies rise from a few to above ten per cent, much higher than expected for several years to come.

The process energy requirements per  $m^2$  for producing p-Si cells are 10 to 100 times larger than for producing a PPV device. In best case, with minimum energy requiring design and data and most beneficial performance and application scenarios (5 per cent efficiency and a lifetime of 5 years), the energy required for production of PPVs is returned about 170 times compared to 10 times for p-Si. However, below 0.1 per cent efficiency or 0.1 year lifetime PPVs has no net electricity production.

The total area requirement indicates the ultimate efficiency of renewable electricity production, including energy losses during manufacturing as well as operation. Even though energy return factors tend to be low for PV in relation to many other renewable energy technologies, the measure of the total area requirement sends a different message. Even if energy losses in production are included, PV converts solar energy more efficiently than most other renewable energy technologies (e.g. biomass combustion). Comparing the required area for electricity generation of p-Si PV and PPV, p-Si cells need only between half and one fifteen of the area PPV requires (for lifetimes above one year and efficiencies above one per cent). However, concerning CO<sub>2</sub> mitigation potentials the economical aspects of electricity production is also essential. If PPVs are cheaper than p-Si devices, the area advantage that p-Si cells have are of less importance in the short run.

The most energy intensive processes during PPV manufacturing are sputtering and vacuum evaporation, if layers are relatively thick (>200-300nm). Printing deposition method, polymer or fullerene production does not influence device energy requirements, not even if polymer synthesis is done under small scale laboratory circumstances.

The energy consumed during CPV manufacturing is paid back 13 to 90 times, i.e. doubled or up to 13 times corresponding p-Si systems. Conversely, the area requirement for generation of 1 MWh electricity is 2 times smaller, for high energy data, and 5 times smaller for low energy data.

Tracker, encapsulation and lenses are the three processes with largest contribution regarding energy requirement for producing CPVs. The tracker is generally the CPV systems' Achilles heel, even if lenses contribute more in one of the analyzed systems. Not only in aspects of large amounts of steel used in the tracker, but also concerning losses due to "bad" tracking, namely about one fourth of the potential production is lost when trackers do not function correctly in e.g. high wind. Trackers account for 21 to 42 per cent of the energy requirements

during manufacturing. However, comparing this to array support materials for silicon PV power plants this value is not extraordinary high. Alsema & Nieuwlaar (2000) state an energy requirement for these materials of  $1800 \text{ MJ/m}^2$  compared to the module manufacturing energy of  $4100 \text{ MJ/m}^2$ .

## 6 Final comments

As we have declared in the introduction, CPV and PPV are two different PV technologies, not only in matter of strategies for cost reduction but also concerning probable markets to penetrate. This assessment's large refractive CPV systems will probably be used in similar way as traditional fossil fuel or nuclear technologies, namely for centralized power generation. This PV technology will therefore compete with today's low cost electricity generation technologies. Contrary, PPV is a PV technology with new features, as flexibility and small weight, which open up not only for traditional markets but also new ones. If one should try to state which one of the technologies, PPV or CPV, that will find large markets first one have to consider more things than energy return factors and area requirements. A comparison should be performed to the energy technologies that these two technologies would replace.

Since the technology definition has great influence of the result, the value of actually seeing products representing the analyzed technology is large. As a consequence, the CPV results could be seen as more certain than the PPV results. To some extent a more extensive sensitivity analysis on PPV have compensated for this. Furthermore, the three system alternatives for CPV are neutrally named system 1, 2, and 3, since the object of this report is to investigate the technology and not specific systems. It is also important to notice that the comparison to p-Si PV technology only should be seen as a reference to the probable performances of PPV and CPV technologies. We have not assessed any development of p-Si PVs in this study.

We would also like to highlight the importance of identifying uncertainties at different technology levels in a study like this. By incorporating uncertainties in data, design and application scenarios we have demonstrated how large the span in results may be. To further decrease uncertainty in these technologies' probable energy performances additional analysis need to be performed. In an attempt to contribute to this continued work we have tried to write this report as transparent and informative as possible. However, one should note that uncertainties are inherent in technology assessments.

## 7 List of references

Admassie, S., F. Zhang, A.G. Manoj, M. Svensson, M.R. Andersson & O. Inganäs (2006). "A polymer photodiode using vapour-phase polymerized PEDOT as an anode" *Solar Energy Materials & Solar Cells* 90:133-141.

Al-Ibrahim, M., H. K. Roth & S. Sensfuss (2004). "Efficient large-area polymer solar cells on flexible substrates" *Applied Physics Letters* 85-9:1481-1483.

Alsema, E.A. & E. Nieuwlaar (2000). "Energy viability of photovoltaic systems" *Energy Policy* 28:999-1010.

Baumann, A.E. (1997). *Life Cycle Assessment of Ground-Mounted and a Building Integrated Photovoltaic Systems*, IEA Expert Workshop on "Environmental Aspects of PV Systems", Utrecht.

Baumann, H. and A-M Tillman (2004). *The Hitch Hiker's Guide to LCA*. Lund, Sweden, Studentlitteratur.

Bett A.W, G. Siefer, C Baur, S. v. Riesen, G. Peharz, H. Lerchenmüller, F. Dimroth (2005), *FLATCON Concentrator PV-technology ready for the market*, presented at the 20th European Photovoltaic Solar Energy Conference, Barcelona, June 2005

Bieder, A., A. Gruniger, Ph. Rudolf von Rohr (2005). "Deposition of SiO<sub>x</sub> diffusion barriers on flexible packaging materials by PECVD" *Surface & Coatings Technology* 200:928-931.

Brabec, C.J. (2004). "Organic photovoltaics: technology and market" *Solar Energy Materials & Solar Cells* 83:273–292.

Burrows, P.E., G.L. Graff, M.E. Gross, P.M. Martin, M.K. Shi, M. Hall, E. Mast, C. Bonham, W. Bennett and M.B. Sullivan (2001). "Ultra barrier flexible substrates for flat panel displays" *Displays* 22:65-69.

Campbell (2005). Eleanor Campbell, Personal Communication. Göteborg, Sweden.

Charton, C., N. Schiller, M. Fahland, A. Holländer, A. Wedel and K. Noller (2005). "Development of high barrier films on flexible polymer substrates" *Thin Solid Films* Article in press.

Flamant, G., J.F. Robert, S. Marty, J.M. Gineste, J. Giral, B. Rivoire & D. Laplaze (2004). "Solar reactor scaling up: the fullerene synthesis case study" *Energy* 29:801–809.

Fletcher Thomas E. (2005), Personal communication, STAR facility, Phoenix, Arizona, USA

Fthenakis, V. & H.C. Kim 2005. Environmental Science Department at Brookhaven National Laboratory (ES&H). Personal communication. New York, USA.

- Gruniger, A. & Ph. Rudolf von Rohr (2004). "Influence of defects in SiO thin films on their barrier properties" *Thin Solid Films* 459:308–312
- Grübler, A. (1998). *Technology and Global Change*. Cambridge, United Kingdom, Cambridge University Press.
- Halls, J. and R. Wilson (2004). *Plastic cells for energy from the sun (PLACES)*. DTI, 04/2091, S/P2/00411/00/REP, CDT Ltd.
- Hayden Herb (2005). Personal communication, Arizona Public Service Company (APS), Phoenix, Arizona, USA.
- Hebgen, P., A. Goel, L.C. Rainey, J.B. Vandersande & J.B. Howard (2005). *Combustion synthesis of fullerenes and fullerene nanostructures*. Available at <http://web.mit.edu/anish/www/JBH-abstract.pdf>. Accessed: 10 December, 2005.
- Hedenqvist, M.S. & K.S. Johansson (2003). "Barrier properties of SiO<sub>2</sub>-coated polymers: multi-layer modelling and effects of mechanical folding" *Surface and Coatings Technology* 172:7–12.
- Hummelen, C., B.W. Knight, F. LePeq & F. Wudl (1995). "Preparation and Characterization of Fulleroid and Methanofullerene Derivates" *Journal of Organic Chemistry* 60:532-538.
- IEA (1998). *Benign Energy? The environmental implications of renewables*. OECD/IEA, Paris, France.
- IEA (2004). Trends in photovoltaic applications in selected IEA countries. <http://www.oja-services.nl/iea-pvps/isr/05.htm>. Accessed: 16 December, 2005.
- IPCC (2001). *Climate Change 2001: Synthesis Report*. Geneva, Switzerland.
- Jonasson K.M. Sandén B.A. Time and scale in life cycle assessment: the case of fuel choice in the transport sector. Accepted for publication in *International Journal of Heavy Vehicle Systems*.
- Komatsu, N., T. Ohe & K. Matsushige (2004). "A highly improved method for purification of fullerenes applicable to large-scale production" *Carbon* 42:163–167.
- Krebs (2005). Frederik Krebs, Danish Polymer Centre at Risø National Laboratory, Personal communication. Risø, Denmark.
- Kroon, J.M., S.C. Veenstra, L.H. Slooff, W.J.H. Verhees, M.M. Koetse, J. Sweelssen, H.F.M. Schoo, W.J.E. Beek, M.M. Wienk, R.A.J. Janssen, X. Yang, J. Loos, V.D. Michailetchi, P.W.M. Blom, J. Knol and J.C. Hummelen (2005). *Polymer Based Photovoltaics: novel concepts, materials and state-of-the-art efficiencies* Presented at the 20th European Photovoltaic Solar Energy Conference and Exhibition, Barcelona, Spain.
- Krätschmer, W., L.D. Lamb, K. Fostiropoulos, D.R. Huffman (1990). "Solid C<sub>60</sub>: a new form of carbon" *Nature* 347:354-358.

- Kurtz Sarah (2005). Personal communication, National Renewable Energy Laboratory (NREL), Golden, USA
- Li, G., V. Shrotriya, J. Huang, Y. Yao, T. Moriarty, K. Emery & Y. Yang (2005). "High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends" *Nature Materials*, Advance Online Publication, [www.nature.com/naturematerials](http://www.nature.com/naturematerials).
- Lysen Erik (2003), Photovoltaics: an outlook for the 21st century. *Renewable Energy World* 6(1): 42-53 (2003).
- Mitsubishi (2005). Plastic films and sheet products from Mitsubishi Chemical Group Companies. <http://www.film-sheet.com/en/index.htm>. Accessed: 10 December, 2005.
- Norquay Technology Inc. (2005), [www.norquaytech.com/uvstabilizers.htm](http://www.norquaytech.com/uvstabilizers.htm)
- NREL Solar Maps (2006), [http://rredc.nrel.gov/solar/old\\_data/nsrdb/redbook/atlas/](http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/). Accessed: 10 April 2006.
- O'Neill M. J., A.J. McDaniel & P.A. Jaster (2002), *Development of terrestrial concentrator modules using high-efficiency multi-junction solar cells*, presented at the 29th IEEE Photovoltaic Specialists Conference, New Orleans, 2002.
- Olson J. M., D. J. Friedman & S. Kurtz (2003), High-Efficiency III-V Multijunction Solar Cell, National Renewable Energy Laboratory, Golden, USA.
- Peharz, G. & F. Dimroth (2004). "Energy Payback Time of the High-concentration PV System FLATCON", 2004.
- Perzon (2005). Erik Perzon, Personal communication. Göteborg, Sweden.
- PlasticsEurope (2005). Eco-profiles of the European Plastics Industry. <http://www.plasticseurope.org/Content/Default.asp?PageID=392#>. Accessed: 11 December, 2005.
- Pyronsolar (2005), Technical description, <http://www.pyronsolar.com/US/tech.htm>.
- Reyes-Reyes, M., K. Kim & D.L. Carrolla (2005). "High-efficiency photovoltaic devices based on annealed poly(3-hexylthiophene) and 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6)C61 blends" *Applied Physics Letters* 87:083506.
- Sandén, B.A., K.M. Jonasson, M. Karlström & A-M. Tillman (2005). *LCA on emerging technologies: A methodological framework*. LCM2005, Innovation by Life Cycle Management, Barcelona, September 5-7.
- Sariciftci, N.S (2004). "Plastic photovoltaic devices" *Materials Today*, September 2004.
- Shah, V.G. & D.B. Wallace (2004). *Low-cost Solar Cell Fabrication by Drop-on-Demand Ink-jet Printing Proc.* IMAPS 37th Annual International Symposium on Microelectronics, Available at: [http://www.microfab.com/about/papers/solarcells\\_IMAPS\\_2004.pdf](http://www.microfab.com/about/papers/solarcells_IMAPS_2004.pdf).

- Shaheen (2005). Sean Shaheen, Personal communication. Golden, Colorado, USA.
- Shaheen, S.E., R. Radspinner, N. Peyghambarian & G.E. Jabbour (2001). "Fabrication of bulk heterojunction plastic solar cell by screen printing" *Applied Physics Letters* 79-18:2996-2998.
- Siemens (2003). Pictures of the Future Fall 2003.  
[http://www.siemens.com/index.jsp?sdc\\_p=t15cz3s5u20o1156373d1187140pFEn1126388flmi1126388&sdc\\_sid=20333128550&](http://www.siemens.com/index.jsp?sdc_p=t15cz3s5u20o1156373d1187140pFEn1126388flmi1126388&sdc_sid=20333128550&). Accessed: 10 December, 2005
- Spanggaard, H. and F.C. Krebs (2004). "A brief history of the development of organic and polymeric photovoltaics" *Solar Energy Materials & Solar Cells* 83:125–146.
- Stema (2005). Ingmar Kjellstedt, Personal communication. Borås, Sweden.
- Swanson R. M. (2003), *Handbook of Photovoltaic Science and Engineering* chap. 11, Sunpower Corporation, Sunnyvale, USA
- Takehara, H., M. Fujiwara, M. Arikawa, M.D. Diener & J. Michael Alford (2005). "Experimental study of industrial scale fullerene production by combustion synthesis" *Carbon* 43:311–319.
- TOPPAN (2005). Packaging materials development and manufacture.  
<http://www.toppan.co.jp/aboutus/overview/accounts/setsume4/english/setsu5.html>. Accessed: 10 December, 2005.
- Tuladhar, S.M., D. Poplavskyy, S.A. Choulis, J.R. Durrant, D.C. Bradley and J. Nelson (2005). "Ambipolar Charge Transport in Film of Methanofullerene and Poly(phenylenevinylene)/Methanofullerene Blends" *Advanced Functional Materials* 15:1171-1182.
- Warmser P. & R. Gaudiana (2003). *Polymer Photovoltaics – Challenges and Opportunities*, Konarka Technologies, Inc, NCPV and Solar Program Review Meeting 2003.
- Webelements (2005). [www.webelements.com](http://www.webelements.com). Accessed: 13 December, 2005.
- Weidema, B.P., T. Ekvall, H.-L. Pesonen, G. Rebitzer, G.W. Sonnemann and M. Spielmann (2004). *Scenarios in Life-Cycle Assessment*, Pensacola FL, USA: Society of Environmental Toxicology and Chemistry (SETAC).
- Wenzel H., M. Haushild & L. Alting (1997). ABB Automation, Environmental Product Declaration, 1997
- Winter-Jensen, B. & F.C. Krebs (2006). "High-conductivity large-area semi-transparent electrodes for polymer photovoltaics by silk screen printing and vapor-phase deposition" *Solar Energy Materials & Solar Cells* 90:123-132.
- Wormser, P. and R. Guadiana (2003). *Polymer Photovoltaics – Challenges and Opportunities* Presented at NCPV and Solar Program Review Meeting 2003.

Yamaguchi M, Takamoto T, Agui T, Kaneiwa M, Araki K, Kondo M, Uozumi H & Hiramatsu M (2004), *Japanese activities of R&D on III-V concentrator solar cells and modules*. Proceeding of the 19th European Photovoltaic Solar Energy Conference and Exhibition, Paris

Zhang, F. (2005). Personal communication. Fengling Zhang at Biomolecular and Organic Electronics, IFM, Linköping University, Linköping, Sweden.

## 8 Appendices

Parameter notations used in calculation are defined locally, i.e. they are given in a table beneath the formula.

### 8.1 Polymer production (laboratory scale)

Data is calculated for a process for producing 2 g of polymer and scaled up to 1 kg. Energy for producing monomers, solvents and catalysts are not included. Calculation are done for three iterative steps,

$$E = 3 \times \frac{\beta}{\alpha \varepsilon} (P_{hp} t_1 + P_{sm} t_r k_1 + P_e t_e k_2 + P_v t_v + P_{hp} t_2), \text{ where estimations are given in Table 12.}$$

**Table 12.** Parameters in calculation.

E	Primary energy	(MJ/kg)
$\alpha$	Conversion factor heat to electricity	0.35
$\beta$	Conversion factor kWh to MJ	3.6
$\varepsilon$	Conversion factor 2g to 1 kg	0.002
$P_{hp}$	Hot plate maximum power	0.63 kW
$P_{sm}$	Stirring motor max power	0.125 kW
$P_e$	Rotary evaporator maximum power	0.125 kW
$P_v$	Vacuum pump maximum power	0.18 kW
$t_1$	Time with max power on hot plate 1	0.05 h
$t_r$	Time for reaction	1 h
$t_2$	Time with max power on hot plate 2	0.05 h
$t_e$	Time for evaporation	0.2 h / 0.25 liter
$t_v$	Time with max power on vacuum pump	0.2 h
$k_1$	Max power utilization factor, stirring motor	0.4
$k_2$	Max power utilization factor, rotary	0.4

### 8.2 VPP PEDOT (laboratory scale)

Calculations for vapor phase polymerization (VPP) are performed as,

$$E_{\min/\max} = \frac{1}{k_{\min/\max}} \left( \frac{P_{hp} t}{A} \times \frac{\beta}{\alpha} + E_{s,\min/\max} \right), \text{ where estimations are given in Table 13.}$$

**Table 13.** Parameters in calculation.

E	Primary energy	(MJ/m <sup>2</sup> )
A	Conversion factor heat to electricity	0.35
B	Conversion factor kWh to MJ	3.6
$P_{hp}$	Hot plate maximum power	0.63 kW
$t_1$	Time with max power on hot plate	0.05 h
A	Deposition area	0.0042 m <sup>2</sup>
$E_{s,\min/\max}$	Max and min primary energy requirements for screen printing	(MJ/m <sup>2</sup> )
$k_{\max}$	Scaling factor, max energy requirements	1.5
$k_{\min}$	Scaling factor, min energy requirements	3

### 8.3 Calculation of C<sub>60</sub> production

Process for producing 0,5 gram C<sub>60</sub> upscaled to 1 kg C<sub>60</sub>. Toluene is combusted with a 0,5% yield of C<sub>60</sub>. 10% is lost in cleaning/separation. Data is calculated from the theoretical energy requirement for combustion. However, heating efficiency is uncertain, so two cases are given as (low) and (high). Results are given in terms of primary energy for production of 1 kg C<sub>60</sub>. Energy for cleaning/separation of C<sub>60</sub> from soot is excluded as well as capital goods. Calculations for production of C<sub>60</sub> are performed as,

$$E = \frac{1}{\varepsilon} \left( \frac{E_h k_{\min/\max}}{s} + \frac{P_v t \beta}{\alpha} + E_T \right), \text{ where estimations are given in Table 14.}$$

**Table 14.** Parameters in calculation.

E	Primary energy	(MJ/kg)
E <sub>T</sub>	Toulene production PER	17.24 MJ/kg (Plastics Europe 2005)
α	Conversion factor heat to electricity	0.35
β	Conversion factor kWh to MJ	3.6
ε	C60 yield from toulene	0.5 per cent (Takehara et al. 2005)
E <sub>h</sub>	Theoretical amount energy to heat and evaporate toluene	0.56 MJ/kg
k <sub>min</sub>	Factor for actual energy to heat, min	2
k <sub>max</sub>	Factor for actual energy to heat, max	4
t	Time for reaction	0.2 h/kg toulene
P <sub>v</sub>	Vacuum pump power	1.0 kW
s	Ratio separated C60	90 per cent (Komatsu et al. 2004)

### 8.4 Calculation of PCBM

PCBM synthesis is calculated from production of C<sub>60</sub> and the energy for producing a polymer in three steps, at lab scale. Procedure for synthesis of PCBM from C<sub>60</sub> includes three steps (Hummelen et al. 1995). High and low values origin from uncertainty in calculation of C<sub>60</sub> production. Energy for production of initial compound is not included. However, C<sub>60</sub> data is cradle-to-gate. Calculations for production of C<sub>60</sub> are performed as,

$$E_{\min} = E_{C_{\min}} + E_{pet}, \text{ where estimations are given in Table 15.}$$

$$E_{\max} = E_{C_{\max}} + E_{lab}$$

**Table 15.** Parameters in calculation.

E	Primary energy	(MJ/kg)
E <sub>Cmin</sub>	C <sub>60</sub> production PER, min	4108 MJ/kg
E <sub>Cmax</sub>	C <sub>60</sub> production PER, max	4257 MJ/kg
E <sub>pet</sub>	PET production PER	45.77 MJ/kg (Plastics Europe 2005)
E <sub>lab</sub>	3 step lab-scale synthesis of polymer PER	2009 MJ/kg

## 8.5 Calculation of plastic encapsulate barrier material

Calculation is done as,

$$E = E_{S \min / \max} T_{A \min / \max} n_{\min / \max} + E_{pet} \delta_p T_{P \min / \max} n_{\min / \max} + E_A \delta_A T_{A \min / \max} n_{\min / \max} ,$$

where estimations are given in Table 16.

**Table 16.** Parameters in calculation.

E	Primary energy	(MJ/kg)
E <sub>Smin</sub>	Sputtering PER, min	0.21 MJ/m <sup>2</sup> /nm
E <sub>Smax</sub>	Sputtering PER, max	0.51 MJ/m <sup>2</sup> /nm
E <sub>Lmin</sub>	Lamination PER, min	0.17 MJ/m <sup>2</sup>
E <sub>Lmax</sub>	Lamination PER, max	0.41 MJ/m <sup>2</sup>
T <sub>Amin</sub>	Aluminum layer thickness, min	10*10 <sup>-9</sup> m
T <sub>Amax</sub>	Aluminum layer thickness, max	60*10 <sup>-9</sup> m
E <sub>pet</sub>	PET production PER	45.77 MJ/kg
		(Plastics Europe 2005)
δ <sub>p</sub>	PET density	1350 kg/m <sup>3</sup>
T <sub>Pmin</sub>	PET layer thickness, min	12*10 <sup>-6</sup> m
T <sub>Pmax</sub>	PET layer thickness, max	75*10 <sup>-6</sup> m
E <sub>Amin</sub>	Aluminum production PER, min	MJ/kg
E <sub>Amax</sub>	Aluminum production PER, max	MJ/kg
δ <sub>A</sub>	Aluminum density	2700 kg/m <sup>3</sup>
n <sub>min</sub>	Number of layers, min	1
n <sub>max</sub>	Number of layers, max	2

## 8.6 Calculation of sputter process energy

Energy requirements for sputtering are calculated from a rough estimation of in-line sputtering process by Henrik Fredrikssen at MC2 Chalmers. Machine is turned off when not operated. Due to uncertainty two cases (high/low) are put forward in terms of process electricity demand and performance. Calculation is done as,

$$E = \frac{\beta}{\alpha} \left( \frac{P_{\min / \max}}{H_{\max / \min} T} \right),$$

where estimations are given in Table 17.

**Table 17.** Parameters in calculation.

E	Primary energy	(MJ/m <sup>2</sup> /nm)
α	Conversion factor heat to electricity	0.35
β	Conversion factor kWh to MJ	3.6
T	Thickness	200 nm
P <sub>min</sub>	Processing power, min	20 kW
P <sub>max</sub>	Processing power, max	30 kW
H <sub>min</sub>	Performance, min	3 m <sup>2</sup> /h
H <sub>max</sub>	Performance, max	5 m <sup>2</sup> /h

## 8.7 Calculation of screen printing

Data is taken from Stema Sceentryckeri, 23 November 2005, Borås Sweden. System operates 12 hours for each heating procedure of dryer. Calculation is done as,

$$E = \frac{\beta}{\alpha} \left( \frac{E_{P\min/\max} + E_{D\min/\max}}{H} \right) n_{\min/\max}$$

where estimations are given in Table 18.

**Table 18.** Parameters in calculation.

E	Primary energy	(MJ/m <sup>2</sup> )
E <sub>Pmin</sub>	Printer energy consumption, min	0.6 kWh/h
E <sub>Pmax</sub>	Printer energy consumption, max	1.5 kWh/h
E <sub>Dmin</sub>	Dryer energy consumption, min	15.4 kWh/h
E <sub>Dmax</sub>	Dryer energy consumption, max	28.6 kWh/h
H	Performance	1836 m <sup>2</sup> /h
n <sub>min</sub>	Number of layers, min	1
n <sub>max</sub>	Number of layers, max	3
α	Conversion factor heat to electricity	0.35
β	Conversion factor kWh to MJ	3.6

## 8.8 Vacuum evaporation

Vacuum evaporation is calculated for e-beam and thermal methods. Calculations are done as,

$$E_B = \frac{\beta}{1000\alpha\tau} [(B_I B_U + B_{If} B_{Uf}) t_B + P_v t_v]$$

$$E_T = \frac{\beta}{1000\alpha\tau} (T_I T_U t_T + P_v t_v)$$

where estimations are given in Table 19.

**Table 19.** Parameters in calculation.

$E_B$	Primary energy E-beam	(MJ/m <sup>2</sup> /nm)
$E_T$	Primary energy Thermal	(MJ/m <sup>2</sup> /nm)
A	Conversion factor heat to electricity	0.35
B	Conversion factor kWh to MJ	3.6
$B_I$	E-beam current	0.2 A
$B_U$	E-beam voltage	10000 V
$B_{If}$	E-beam filament current	20 A
$B_{Uf}$	E-beam filament voltage	6 V
$T_I$	Thermal current	240 A
$T_U$	Thermal voltage	0.7 V
$P_v$	Vacuum pump power	900 W
$t_v$	Vacuum pump operation time	1/6 h
$t_B$	E-beam time	1/6 h
$t_T$	Thermal time	1/2 h
$\tau$	Thickness	200 nm