Presented at the Renewable Energy 2006
9-13 October 2006, Makuhari Messe, Chiba, Japan

DYE SENSITISED SOLAR CELLS FOR LARGE-SCALE PHOTOVOLTAICS; THE DETERMINATION OF ENVIRONMENTAL PERFORMANCES

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This paper describes the results of a Life Cycle Analysis (LCA) study of Dye Sensitised Solar Cells (DSC). The results are largely based on the operational experiences with a baseline for the semi-automated manufacturing of DSC devices. This baseline was installed in 2002 at ECN Solar Energy (Petten, The Netherlands). Results are compared with other energy technologies.

Keywords: Life Cycle Analysis, Dye Sensitised Solar Cells

INTRODUCTION

Photovoltaic systems inherently generate pollutants over their entire life-cycle. To study the environmental impact of products, an inventory of all energy and material inputs for the product is made, including all emissions to the environment. This life cycle inventory is subsequently used to calculate the size of various impact indicators, such as land-use, depletion of resources, contribution to acidification, ozone layer depletion, ecotoxicity and greenhouse gas emissions.

Detailed LCA studies of photovoltaic (PV) systems have become available [1,2]. These studies are mainly concerned with crystalline silicon and thin film-silicon PV technologies. An important conclusion from these studies is that the product use phase of PV systems has negligible environmental impact. Such LCA studies therefore focus on the manufacturing and end-of-life phases of PV systems.

The first LCA study of dye-sensitized solar cells was published by Greijer *et al*. in 2001 [3]. In their analysis, a liquid junction glass-based dye PV system was used for delivering electricity to the grid. Their study ranked carbon dioxide emission as most relevant environmental indicator for DSC.

This paper describes the results of a LCA study of DSC with the purpose to identify environmental critical issues and find options for improvement of dye cells. The results of this study are largely based on the operational experiences with a baseline for the semi-automated manufacturing of DSC devices. This baseline was installed in 2002 at ECN Solar Energy (Petten, The Netherlands [4]). Results are compared with other energy technologies, including present- and future crystalline silicon based photovoltaics.

METHODOLOGY

The environmental life cycle assessment has been carried out according to ISO14040 standard, using SimaPro 7 software with the database Ecoinvent 1.2 (corrections made for list of errors as of 16 March 2006). Most dominant is the impact due to the use of primary energy for the materials in the manufacturing phase. This is calculated by using the Cumulative Energy Demand version 1.03 method. In the calculations, the energy mix is taken as is used by the European Union for the Co-ordination of Transmission of Electricity. This is a mix of coal, gas, oil, nuclear, hydro, biomass and wind energy.

The life cycle greenhouse gas emissions are used to determine the potential contribution to greenhouse gas mitigation. This indicator is calculated by determining the total emission of greenhouse gases over the system's life cycle and dividing this by the total amount of electricity generated by the system over its lifetime. Another useful indicator for renewable energy technologies is the energy pay-back time (EPBT). The EPBT value provides the number of years the energy system has to generate electricity in order to compensate the energy invested during production of the system. Both the greenhouse gas emissions and EPBT are strongly correlated by the geographic location of the PV system via the annual solar irradiation level.

We assume that DSC modules are used to deliver electricity to the grid and are rooftop installed. Hence, material and energy usage and emissions are ascribed to the amount of kWh produced during the operational lifetime of the module. A performance ratio of 0.75 is assumed. This ratio corrects for additional PV system losses due to inverter, not-optimal orientation, temperature fluctuations and other factors that are not taken into account by the DSC module nominal power rating. A performance ratio of 0.75 is normally used for crystalline silicon PV. Note that the actual performance ratio of DSC systems may vary considerably with system design, shading and temperature, among other factors.

The end-of-life phase and options for recycling are not included in this work. Recycling of energy-intensive materials such as TCO-glass can decrease the primary energy requirements considerably, but at present there is no practical experience with end-of-life and recycling of DSC modules.

As a typical example, we selected the liquid junction glass-glass laminate DSC version with a "current-collecting" design. To this end, a Ag-grid on the front and back TCO-electrode is used to improve current collection and, hence, the fill factor [4]. Instead of using such a metal grid for current collection, monolithic series connection can be used [5]. In our study, glass sealing of the front- and back electrode is carried out using hotmelt/polypropylene gaskets in a low-vacuum laminator. The use of an aluminum frame on the glass-glass laminate is assumed to make results comparable with LCA studies on crystalline silicon photovoltaics [1]. For similar reason, the materials and energy input for inverter and cabling ("Balance of System") were also taken from this same study. Note that in reality, framing and BOS technology are not yet wel defined for large scale dye cell application, and this may be different in future applications as compared to crystalline silicon based photovoltaics.

Table 1 provides the material and energy streams required for the manufacturing 1 m^2 of this type of DSC module [4]. The process energy is calculated based on the power consumption (in kWh) of manufacturing apparatus used in the ECN 10x10 cm baseline, assuming maximal throughput of 30x30 cm DSC devices for each process step and no energy consumption during idle time of the specific instrument. The maximum throughput in our baseline, for a single apparatus, is determined by the laminating step, and is approximately 40 glass-glass laminates/hour (30x30 cm).

RESULTS AND DISCUSSION

Environmental impact of DSC substrates

DSC devices can be manufactured on different types of substrates. Unfortunately, no LCA data is available for titanium foil, polyimide or fluorinated hydrocarbon material. These materials are under consideration for use as substrate or encapsulant of DSC modules. We therefore selected glass, stainless steel and PET (PolyEthylene Teraphtlalate) as potential substrates for DSC modules and which are included in the Ecoinvent database. Fig. 1 shows the normalized impact indicators for a unit area of these materials,. Stainless steel has by far the largest impact on toxicity, which is due to chromium VI in stainless steel. A substantial fraction of fossil fuel is used for the manufacturing of glass and, hence the impact indicators for glass are mainly influenced by the energy usage in the manufacturing of this glass.

Materials (available in LCI database)	g/m2 module	Comment
Solar glass, low-iron, at regional storage/RER U	15,000	2x 3 mm thick
Tin, at regional storage/RER U	1,9	For TCO
Metallization paste, silver	7,2	for screenprinting Ag metal grid
Titanium dioxide, production mix, at plant/RER U	16	
Chemicals organic, at plant/GLO U	50	terpineol in TiO_2 screenprint paste and other chemicals
Chemicals organic, at plant/GLO U	3,5	ethylcellulose in TiO_2 synthesis
Platinum, at regional storage/RER U	0,1	ruthenium not in database,
Acetone cyanohydrin, at plant/RER U	20	acetonitrile not in database
Platinum, at regional storage/RER U	0,05	Pt catalyst
Polyethylene, HDPE, granulate, at plant/RER U	20	hotmelt foil
Polyester resin, unsaturated, at plant/RER U	20	
Chemicals organic, at plant/GLO U	0,16	Junction box
Iodine, in ground	0.45	In liquid electrolyte
Electricity		
Electricity, medium voltage, consumption UCTE, at grid/UCTE U	13 kWh/m^2	Electricity consumption + 10% overhead

Table 1. Material and energy use for the manufacturing of 1 m^2 glass-glass dye solar cells (based on ECN process steps, total area).

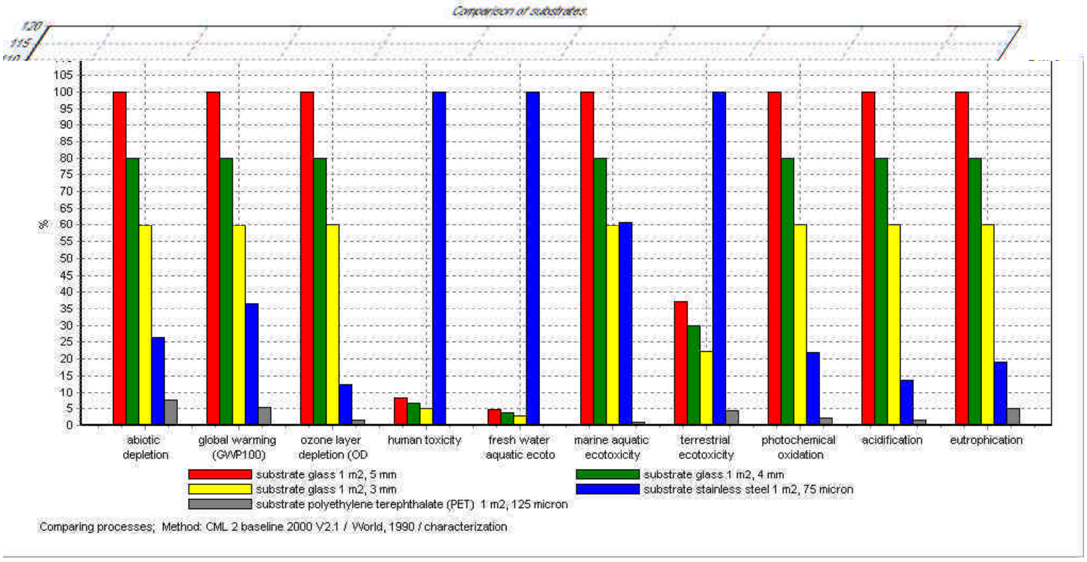


Fig. 1. Environmental impact indicators calculated for different substrates (3-4-5-mm glass, 125 µm stainless steel, 75 µm PET)

Energy payback time of DSC

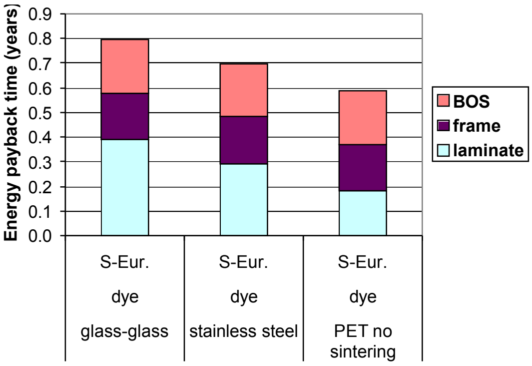
The energy payback times of glass-glass DSC devices have been calculated for 3 irradiation levels, low (Netherlands/Germany), medium (South-Europe) and high irradiation (Sahara desert), according to the calculations in Table 2. The EPBT values are 1.3, 0.8 and 0.6 years, respectively.

In Figure 2, the EPBT values have been plotted for different DSC configurations. A medium irradiation level was used in this calculation (South-Europe). For glass and stainless steel, a high temperature sintering was used, whereas a low temperature sintering approach was used for PET-substrate. An equal technical performance of these 3 DSC configurations was assumed. In reality, low temperature routes for DSC fabrication will most likely result in lower conversion efficiencies. It can further be seen from Figure 2 that, under the assumptions mentioned above, the use of plastic substrate lowers the EPBT considerably, from 0.8 (glass-glass), 0.7 (stainless steel) to 0.6 years (PET).

Table 2. Energy payback calculation of glass-glass DSC devices for 3 solar irradiation regimes

	low irradiation (NW Europe)	**medium irradiation (S-Europe)**	**High irradiation (Sahara desert)**
Energy input per kWp, including frame & BOS	11740 MJ_p/kWp	11740 MJ_p/kWp	11740 MJ_p/kWp
Irradiation	1000 kWh/m^2/yr	1700 kWh/m^2/yr	2190 kWh/m^2/yr
Performance ratio	0.75	0.75	0.75
Annual yield	750 kWh/kWp/yr	1275 kWh/kWp/yr	1642 kWh/kWp/yr
Energy output 1 kWh_e = 11.6 MJ_p	8700 MJ_p/kWp/yr	14700 MJ_p/kWp/yr	19053 MJ_p/kWp/yr
Energy payback time = energy input/output	1.3 years	0.8 years	0.6 years

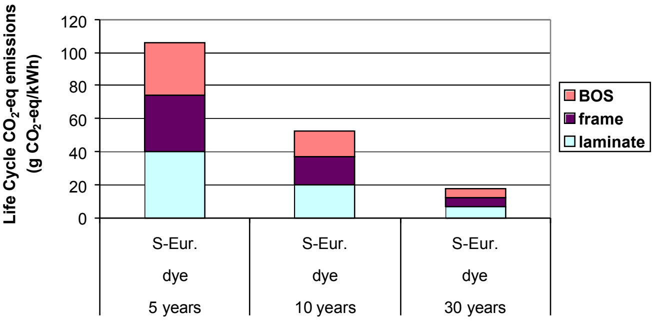
Fig. 2. Energy payback time for DSC modules as a function of substrate type.



Greenhouse gas emissions of DSC

In order to calculate the greenhouse gas equivalent emissions, the operational lifetime of the dye module must be defined. We consider 5 years as a minimum lifetime required for introduction of grid-connected DSC modules, provided that costs are strongly competitive with respect to other PV technologies such as amorphous and crystalline silicon. For calculating the amount of CO_2-equivalent greenhouse gas emissions per kWh produced electricity, we assumed operational lifetimes of 5, 10 and 30 years, a glass-glass DSC module with 8% efficiency (total area, AM1.5) and an irradiation level of 1700 $kWh/m^2/yr$ (South Europe). Note that thirty years lifetime is normally used in similar calculations for crystalline silicon. Figure 3 summarizes the results; obviously, the greenhouse gas emissions are strongly related to the lifetime of the DSC module. The ranges calculated in this study resemble the greenhouse gas equivalent emissions reported by Greijer for glass-based DSC modules [3]. They calculated 19-47 g CO_2/kWh for a lifetime of 20 years at 2190 $kWh/m^2/yr$. The range in their study depends on DSC module manufacturing energy and AM1.5 conversion efficiency; the authors varied the efficiency of the active area between 7-12% and the manufacturing energy between 100-280 kWh/m^2.

Fig. 3. Green House Gas emissions of glass-glass DSC modules as function of lifetime (location S-Europe)



To put the results in more perspective, Table 3 provides the greenhouse gas emissions of different energy technologies. As can been seen from this Table, the uncertainty in life cycle greenhouse gas emissions is relatively large for photovoltaic technologies such as DSC which is a result of the uncertainties in the assumptions such as on lifetime and process energy. Nevertheless it can be concluded that dye cells show a good potential for greenhouse gas mitigation.

Table 3. Greenhouse gas emissions of energy technologies[a]

Energy Technology	g CO_2 eq./kWh
Combined cycle gas turbine	400
European electricity supply	588
Wind energy	8
Biomass	20
Cryst. Silicon PV	15-32[b]
DSC (this study, glass-glass, South Europe)	20-120 (depending on lifetime)

[a]E. Alsema, Critical issues in the Life Cycle Assessment of Photovoltaic Systems, Workshop on Life Cycle Analysis and Recycling of Solar Modules- The Waste Challenge, Brussels, 18-19 March 2004.[b]E. Alsema *et al.*, 21st EPVSEC, Dresden, 2006.

Depletion of resources

The scarce materials in the case of DSC include ruthenium (which is an essential part of the dye commonly used) and silver (used in the screenprinted metal-grid in case of 'current collection' design used for this study). Based on economic reserves of ruthenium as known in 1998, Andersson calculated that, if all of these reserves would be used for the production of DSC modules, the theoretical maximum installed DSC power amounts to approximately 6 TWp [6]. In reality, a large part of the ruthenium reserves will be used for other applications than DSC, such as electronic circuits, process catalysts and as electrode coating for electrochemical applications. Promising efficiencies have already been reported for DSC based on fully organic dyes so in future DSC technology may not require Ru-containing dyes for efficient and stable operation [7].

CONCLUDING REMARKS

In the absence of any information on real (i.e., large scale commercial) DSC manufacturing, we extrapolated information from our semi-automated DSC baseline.
It turns out that the dominant environmental impact arises from energy consumption for the preparation of materials (mainly substrates) and for module manufacturing. The glass substrate in particular has a major effect on the energy requirement. This situation can be improved by using thin-glass or other types of substrates, such as metal- or polymer-foil. A further improvement can be obtained by adapting low-temperature approaches for module preparation, such as the pressing or microwave sintering of TiO_2 nanoparticles. Nevertheless, it must be stressed that, up to now, glass-based DSC cells and high-temperature processing give much better DSC performances and stability, which makes the comparison of substrates or processing routes rather premature and artificial.

We consider our LCA study conservative with respect to module manufacturing since the energy consumption of the manufacturing steps would be more energy efficient upon up scaling. In addition, DSC modules using metal- or polymer-foil substrates would probably not require an aluminum framing, reducing the energy requirement even further. Recycling of TCO-glass may reduce the energy requirements also drastically, but there is no practical experience yet with recycling of DSC components.

Ultimately, the Energy PayBack Time is largely determined by the framing and BOS components. Leaving out the alu frame, an EPBT of 0.3-0.4 year will be within reach if the PV system is roof-top installed in South-Europe. Of this, the DSC module contributes only 0.2 year. The greenhouse gas emissions are strongly correlated with the operational lifetime of DSC modules, and varies between 20-120 g CO_2 eq. /kWh. This is within the range of new generations crystalline silicon PV modules. Outdoor stability is thus the key factor in order to reach environmental benign DSC photovoltaics.

ACKNOWLEDGEMENT

This work was funded by the Dutch Ministry of Economic Affairs. The contribution of Paul Sommeling and Jan Kroon are thankfully acknowledged.

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