ENVIRONMENTAL LIFE CYCLE ANALYSIS OF DYE SENSITIZED SOLAR DEVICES; STATUS AND OUTLOOK

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ABSTRACT: This paper summarizes the results of an environmental life cycle assessment (LCA) study of dye sensitized solar cells (DSC). The input data for this LCA study are largely based on the baseline for the semi-automated manufacturing of liquid junction, glass-glass based DSC devices at ECN Solar Energy (Petten, The Netherlands). Results show that the largest contribution to the environmental impact production stems from the use of glass substrate. Further contributions arise from the energy consumption during production of DSC modules and the use of the ruthenium , platinum and silver in the DSC modules.

The energy payback time in Southern Europe for a complete photovoltaic system with 8% efficient DSC modules is approximately 0.8 years.The life-cycle greenhouse gas emissions can be as low as 20 g CO_2-eq per kWh electricity produced, depending of the lifetime of the DSC systems.

Keywords: dye-sensitized, environmental effect, module manufacturing

1 INTRODUCTION

To study the environmental impact of products, an inventory of all energy and material inputs for the product should be prepared, and the emissions to the environment. Subsequently, this life cycle inventory can be used to calculate the size of various environmental impact indicators, such as depletion of resources and greenhouse gas emissions.

Photovoltaic systems inherently generate pollutants over their entire life-cycle. 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 that are already commercialized. One important conclusion from these studies is that, when in use, PV systems have negligible environmental impact. LCA studies of PV 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 the most relevant environmental indicator for DSC.

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

2 METHODOLOGY

2.1 LCA

We assume that DSC modules are used to deliver electricity to the grid and the DSC PV systems are rooftop installed. Hence, emissions, material and energy usage are ascribed to the amount of kWh produced during the operational lifetime of the DSC module. A performance ratio of 0.75 is assumed. This ratio corrects for 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.

A useful parameter for comparison of 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 for the energy used for the production of the complete system. The energy input during manufacturing is calculated by using the Cumulative Energy Demand (CED) method version 1.03.

The life cycle greenhouse gas emission, expressed as CO_2-equivalents, can be used to compare the potential contribution of renewable energy technologies for greenhouse gas mitigation. This parameter 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. This is calculated by using the IPCC 2001 GWP100a method.

Both the EPBT and the greenhouse gas emissions are correlated to the annual solar irradiation and therefore to the geographic location of the PV system..

The environmental life cycle assessment has been carried out according to ISO14040, using SimaPro 7.0.2 software with the database Ecoinvent 1.3. The largest environmental impact was found to be due to the use of primary energy for the manufacturing of materials. For these calculations, the energy mix is taken as it is representative for the European Union for the Co-ordination of Transmission of Electricity (UCTE). This is a mix of coal, gas, oil, nuclear, hydro, biomass and wind energy.

No data are available for process emissions during the manufacturing of dye cells, so this is not included in the analysis. Typically, the manufacturing steps involve low-temperature, non-vacuum processes such as screenprinting, drying and lamination. Organic solvents are commonly used but these can easily be recovered or mitigated. Naturally, 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. Therefore, the end-of-life phase and options for recycling are not included in this work.

As a typical example, we selected the liquid junction glass-glass laminate DSC version with a "current-collecting" design. In this configuration, a silvergrid on the front and back TCO-electrode is used to improve current collection and, hence, the fill factor [4].Alternatively, 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. In order to make the results comparable with LCA studies on crystalline silicon photovoltaics [1] the use of an aluminum frame on the glass-glass laminate is assumed. For similar reason, the materials and energy input for inverter and cabling ("Balance of System") were taken from this same study. Note that in reality, framing and BOS technology are not yet well defined for large scale dye cell application, and this may be very different as compared to crystalline silicon based photovoltaics.

DSC devices can be manufactured on different types of substrates, such as TCO-glass, titanium foil and special polymer foils. Reliable life cycle inventory data for titanium foil, polyimide or fluorinated hydrocarbon material is not available. We therefore selected glass, stainless steel and PET (PolyEthylene Teraphtalate) as potential substrates for DSC modules; these materials are included in the Ecoinvent database.

Table I provides the average material and energy streams required for the manufacturing of 1 m^2 of glass-glass, liquid junction DSC module [4]. The process energy is calculated based on the power consumption (in kWh) of manufacturing apparatus used in the ECN baseline, assuming maximal throughput of 30x30 cm^2 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^2).

Life cycle inventory data for the production of Transparent Conducting Oxide (TCO) layers is not available in the EcoInvent database. For this study, it is assumed to take place by Atmospheric Pressure Chemical Vapor Deposition (APCVD) via [6].

$SnCl_4 + 2H_2O \rightarrow SnO_2 + 4\ HCl$

The yield of this reaction is 25-45% [personal communication Karel Spee, TNO, the Netherlands]. We assumed 35% in our calculation. The $SnCl_4$ is produced via :

$Sn + 2\ Cl_2 \rightarrow SnCl_4$ (assuming 95% yield)

according to [7].

A doping of 0.2 weight% F in the SnO_2:F is assumed [8] by using HF (95% yield).

3 RESULTS AND DISCUSSION

3.1 Environmental impacts of DSC module (glass substrate)

From figure 1 it can be seen that large part of the environmental impact of DSC is coming from the glass substrate. The production of glass consumes a relative much of energy. This situation can be improved by using thin glass or other types of substrates, such as metal- or polymer foil.

Also the direct energy consumption in the production process of the DSC modules contributes to the environmental impact. The steps that use most of the energy are the sintering of the TiO_2 layer and the glass-glass lamination.

Furthermore the use of ruthenium, platinum and silver contribute to the environmental impact of DSC.

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

Life Cycle Inventory data used in this analysis	g/m^2 module	Comment
Resources		
Iodine, in ground	0.45	In liquid electrolyte
Electricity		
Electricity, medium voltage, production UCTE, at grid/UCTE U	12 kWh/m^2	Electricity consumption + 10% overhead
Transport		
Transport, lorry 32t/RER U	7.63 tkm	Assuming 500 km distance
Materials		
Solar glass, low-iron, at regional storage/RER U	15000	Glass 2 x 3 mm thickness
Tin oxide deposition by APCVD (own estimation)	1 m^2/m^2 module	SnO_2:F TCO layer of 500 nm thickness
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 electrode
Polyethylene, LLDPE, granulate, at plant/RER U	23	Hotmelt foil of LLDPE
Polyester resin, unsaturated, at plant/RER U	130	Protective foil of polyethylene
Chemicals organic, at plant/GLO U	160	Junction box
Waste treatment		
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	18.6	Waste of hot melt foil to municipal incineration
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	130	Protective foil of hot melt foil to municipal waste incineration

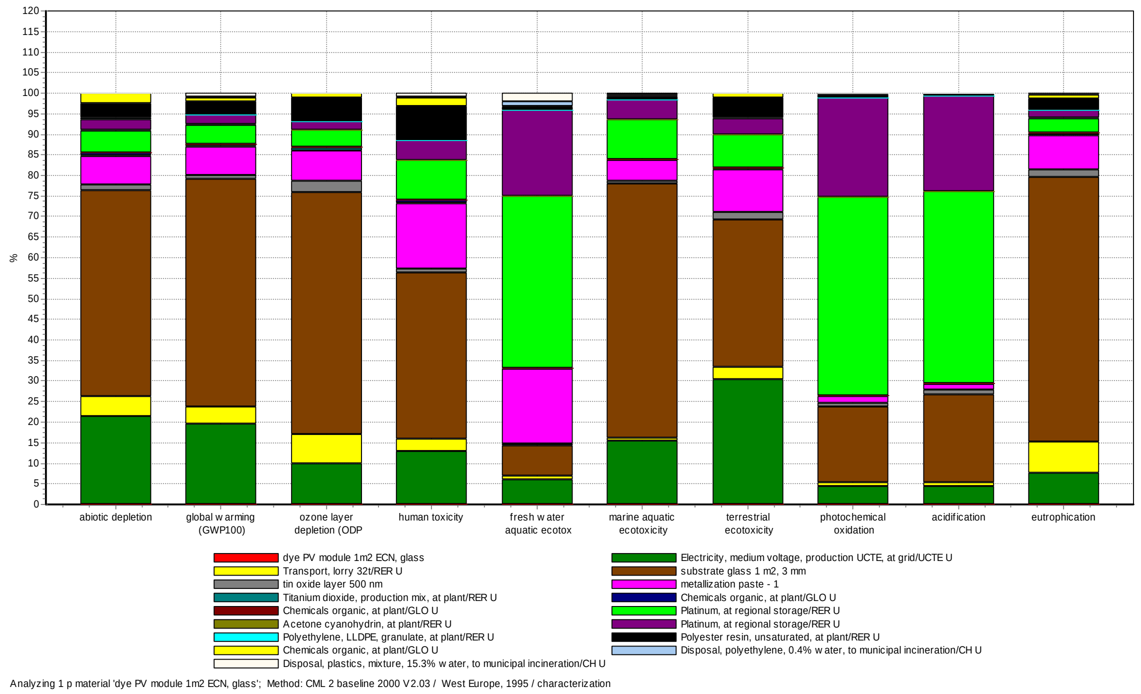

Figure 1: Environmental impact assessment of DSC glass-glass module using CML 2 baseline 2000 method

3.2 Energy payback time of DSC

The energy payback times of glass-glass DSC devices have been calculated for 3 irradiation levels according to the calculations in Table II. The EPBT values are 1.4, 0.8 and 0.6 years for North-West Europe, South Europe and Sahara desert respectively. This compares favorably with crystalline silicon which, for instance, has an EPBT of 1.5 years for PV systems with multicrystalline silicon modules installed on roofs in Souther Europe.

In Figure 2, the EPBT values have been plotted for different DSC substrates. An equal technical performance of the DSC configurations was assumed. A medium irradiation level was used in this calculation (South Europe). For glass and metal substrates, a high (450°C) temperature sintering was used, whereas a low (< 110°C) temperature sintering approach was used for PET-substrate. In reality, high temperature routes for DSC fabrication at the moment results in 2-3x higher conversion efficiencies. The main reason for this is more efficient electron transport in the TiO_2 nanoparticles layer upon high temperature treatment. High temperature treatment may also have a beneficial purification effect of the TiO_2 surface.

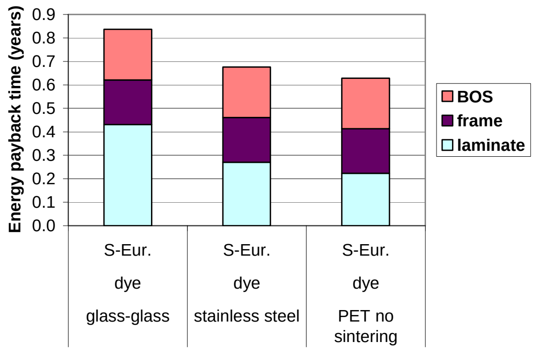

Figure 2: Energy payback time in Southern Europe for PV systems using DSC modules with different substrates (8% module efficiency).

Table II: Energy payback calculation of glass-glass DSC devices for 3 solar irradiation regimes (8% module efficiency)

	Low irradiation (NW Europe)	Medium irradiation (S Europe)	High irradiation (Sahara desert)
Energy input per kWp including frame and BOS	12365 MJ_p/kW_p	12365 MJ_p/kW_p	12365 MJ_p/kW_p
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	1.4 years	0.8 years	0.6 years

3.3 Greenhouse gas emissions of DSC

In order to calculate the CO_2 equivalent emissions per kWh produced, the operational lifetime of the DSC 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. 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.. The greenhouse gas emissions/kWh are linearly related to the lifetime of the DSC module. The ranges calculated in this study resemble the CO_2 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 irradiation level of 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.

To put the results in more perspective, table III provides the greenhouse gas emissions of different energy technologies. As can be 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 DSC show a good potential for greenhouse gas mitigation.

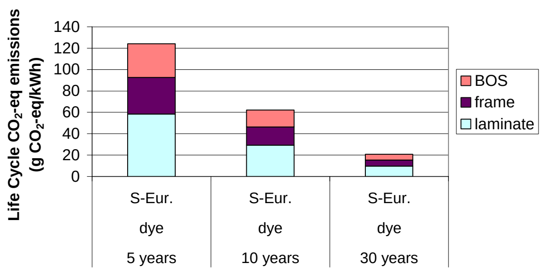

Figure 3: Green House Gas emissions of glass-glass DSC modules as function of lifetime (location S-Europe)

Table III: Greenhouse gas emissions of energy technologies. Data from EcoInvent 1.3 and [2,9].

Energy technology	g CO_2-eq/kWh
Combined cycle gas turbine	400
European electricity supply (UCTE)	484
Wind energy	11
Biomass CHP	45
Crystalline silicon PV (S-Europe)	29-36
DSC (this study, glass-glass, S-Europe)	20-120 (depending on lifetime)

3.4 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, 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 [10]. In reality, 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. But despite these other Ru usages, DSC has potential to become a TWp energy technology, in particular when materials will be recycled. Additionally, 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 [11].

4 CONCLUSIONS

In the absence of any information on real (i.e., large scale commercial) DSC manufacturing, we extrapolated information from the semi-automated DSC baseline at ECN Solar Energy. It turns out that the dominant environmental impact arises from energy consumption for the preparation of materials (mainly glass 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 change to 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 premature.

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 aluminum frame, an EPBT of 0.6 year will be within reach if the PV system is roof-top installed in South-Europe. Of this, the DSC module contributes only 0.4 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 long-term stability is thus the key factor in order to reach environmental benign DSC photovoltaics.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] E.A.Alsema, M.J.de Wild-Scholten, Environmental impacts of crystalline silicon photovoltaic module production, *Proceedings of the MRS Fall 2005 meeting, Symposium G, Boston, U.S.A.* (2005) .

[2] E.A.Alsema, M.J.de Wild-Scholten, V.M.Fthenakis, Environmental impacts of PV electricity generation - a critical comparison of energy supply options, *21st European Photovoltaic Solar Energy Conference, Dresden, Germany* (2006) 3201 .

[3] H.Greijer, L.Karlson, S.E.Lindquist, A.Hagfeldt , Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system, *Renewable Energy* **23** (2001) 27, http://netserv.ipc.uni-linz.ac.at/~dieter/DsWeb/Lit/SSC/RenE23(01)27_Hagfeld.pdf.

[4] M.Späth, P.M.Sommeling, J.A.M.vanRoosmalen, H.J.P.Smit, N.P.G.vanderBurg, D.R.Mahieu, N.J.Bakker, J.M.Kroon , Reproducible manufacturing of dye-sensitized solar cells on a semi-automated baseline, *Prog. Photovolt. Res. Appl.* **11** (2003) 207.

[5] A.Kay, M.Grätzel, Low cost photovoltaic modules based on dye sensitized nanocrystalline titanium dioxide and carbon powder, *Sol. Energy Mater. Sol. Cells* **44** (1996) 99.

[6] K.Spee, APCVD coatings on glass. Focus on transparent conducting oxides (presentation), *8th ESG Conference of Glass Science and Technology, Sunderland, United Kingdom* (2006).

[7] G.G.Graf, Tin, tin alloys, and tin compounds, In: *Ullmann's Encyclopedia of Industrial Chemistry*(2005) .

[8] R.Shiratsuchi, S.Hayase, Farbstoff-sensibilisierte Solarzelle, (assignees: Kyushu Institute of Technology, Kitakyushu, Fukuoka, Japan), **DE 10 2005 033 266 A1** (16-2-2006).

[9] M.J.de Wild-Scholten, E.A.Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production - Status 2005/2006 (Excel file) , **ECN-E--07-026** Energy research Centre of the Netherlands, Petten, the Netherlands, (2007), http://www.ecn.nl/publicaties/default.aspx?nr=ECN-E--07-026.

[10] B.A.Andersson, Materials availability for large-scale thin-film photovoltaics, *Prog. Photovolt. Res. Appl.* **8** (2000) 61.

[11] K.Hara, T.Sato, R.Katoh, A.Furube, T.Yoshihara, M.Murai, M.Kurashige, S.Ito, A.Shinpo, S.Suga, H.Arakawa, Novel conjugated organic dyes for efficient dye-sensitized solar cells, *Adv. Funct. Mater.* **15** (2005) 246.