LIFE CYCLE ASSESSMENT OF HETEROJUNCTION SOLAR CELLS AND MODULES

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ABSTRACT: Heterojunction solar cells have demonstrated high efficiencies and are also viewed as potentially highly sustainable. A life-cycle assessment (LCA) was performed to compare the sustainability of heterojunction (HJ) solar cells, as developed in the HETSI project (FP7-ENERGY-2007-1-RTD), to conventional mono-crystalline Si solar cells. This calculation resulted in a comparison of the cumulative energy demand (MJ) and the global warming potential (kg-CO_2 eq) for HJ cells versus the mono-crystalline cells. The energy payback times (EPBT) of modules of two different HJ cell designs was found to be 1.2 and 1.2 years, while that of a ‘standard’’ mono-crystalline Si module was 1.5 years. The carbon footprint for module fabrication for the mono-crystalline Si module, and the two modules with slightly different HJ cell designs were: 0.9, 0.8 and 0.8 kg CO_2 equivalents/ Wp, respectively. Assuming a southern Europe illumination of 1700 kWh/m^{2}yr, a 75% performance ratio and a 30 year lifetime and no performance degradation, these values may also be expressed as 24, 20 and 20 g-CO_2 equivalent/kWh. The higher efficiency of the HJ solar cells factors into a more favourable energy payback time, and a lower carbon footprint (per Wp or per kWh). A discussion of the cumulative energy demand and environmental impact of the manufacturing processes, together with an outlook on resource depletion, points out the materials and processes which require further development for future manufacturing requirements of lower energy use and lower costs. This is the first time an LCA of c-Si/ a-Si:H HJ solar cell technology is presented.

1 INTRODUCTION

As R&D institutes and the PV industry strive for high-efficiency cell concepts as well as more energy efficient processing, many c-Si/a-Si:H HJ solar cell designs and processes are currently being investigated. Some promising process flows for the industrial fabrication of these type of solar cells have been identified in the European heterojunction project, HETSI. In this work, life cycle assessment (LCA) has been performed on these process flows in order to evaluate the expected environmental impact and the energy pay-back time of the new generation of c-Si/a-Si:H heterojunction solar cells.

2 METHODOLOGY

2.1 Environmental Impact Assessment

The life cycle assessment was performed using Simapro software (version 7.2.4) in conjunction with the ecoinvent database (version 2.2).

2.2 Data

The heterojunction cells developed, on the laboratory scale, in the HETSI project attained an efficiency of greater than 19%. The encapsulation power loss to module was assumed to be 5%. Energy data for those industrial processes not included in ecoinvent were gathered from market surveys of the relevant industrial equipment, or from HETSI industrial partners. Total area module efficiencies were taken as 14% for the conventional mono-crystalline Si module and 16.4% for the heterojunction modules.

3 CELL AND MODULE PROCESS FLOWS

3.1 Cell Processes

In this analysis, two heterojunction cell designs have been compared to a standard mono-crystalline p-diffused H-pattern solar cell.

For all three cell types, a mono-crystalline Cz Si wafer (180 μm thickness) was used. The dopant for the ingot/crystal growing of either *n* or *p* type wafer is a small quantity that does not contribute significantly to the energy use, or carbon footprint of the wafering process and so was not included in the calculation. The feedstock consists of metallurgical grade silicon purified with the Siemens process. The standard mono-crystalline Si cell process includes a standard alkaline texturing process. The HETSI cell process also uses an alkaline texturing step, but supplements it with additional cleaning steps. The standard cell process includes formation of the emitter with high temperature diffusion of a dopant into the wafer, subsequent glass removal and a plasma enhanced chemical vapour deposition (PECVD) process for deposition of the Si_3N_4 layer to passivate the surface and to function as an anti-reflection coating.

The *i,n* or *p* a-Si layers which form the heterojunction and backside passivation layers are also deposited by PECVD. In this study, the PECVD process for the deposition of a-Si was taken to require the same energy as the PECVD process for the deposition of Si_3N_4, only linearly scaled with the thickness of the layer. The PECVD process is based on nominal through-puts and average power consumption for the deposition of Si_3N_4 with substrate temperatures in the range of 250-550°C. [1] The PECVD of a-Si occurs at lower average temperatures, thus requiring less energy input. The cleaning of PECVD equipment is required from time to time. This is achieved with etching with fluorinated gases or ammonia, or by a mechanical process. The use of fluorinated gases or ammonia for cleaning, without a proper abatement system, leads to emission of greenhouse gases.[2] According to a recent market survey, about 1/3 of the 34 PECVD systems included use fluorinated gases or ammonia for cleaning, while the other 2/3 use a mechanical process.[2] Because this depends on the specific system used, these emissions have not been included in this analysis.

Two different heterojunction cell structures were investigated: Hetsi-1 has 90 nm thick layer of ITO deposited on the front-side, and a 300 nm thick layer of ZnO deposited on the back. Hetsi-2 has ITO deposited on both sides. The metallization of the front side requires a double print (actually 1.6 times) of the standard amount (normally used at high temperature) silver paste. Hetsi-1 has a sputtered Al (2 µm) closed backside, and Hetsi-2 has an open backside single silver print. The process flows for the HETSI cells, as well as the ‘standard’ mono-x-Si cell are summarized in Table I.

The Hetsi process replaces the high temperature firing step of the standard process with a 200°C curing step. In order to model this curing step, a survey was conducted of industrial curing ovens. The data that was available was for a drying oven in an automated screen printing line.[3] The data used in here describes the average power consumption for a 2 m long conveyor belt dryer, operating at 180 - 200 °C, providing the cells a drying time of 20 seconds. The HETSI cells require much longer drying times. The energy use for a belt oven with a high throughput is typically greater than that with low throughput because the belt has to be reheated at a higher frequency. Therefore, this data may be on the conservative side.

Table I: Process flows for HETSI vs. Standard cells

	Standard p-mono x-Si	**HETSI 1**	**HETSI 2**
Wafer	Mono x-Si	Mono x-Si	Mono x-Si
Texturing /cleaning	Standard clean	HETSI clean	HETSI clean
Cell structuring	High-temp. P-diffusion PSG removal PECVD: Si_3N_4 (80 nm)	Low-temp. PECVD: *i,n,p* a-Si (40 nm) CVD: ZnO (300 nm) Sputtering: ITO (90 nm)	Low-temp. PECVD: *i,n,p* a-Si (40 nm) Sputtering: 2 x ITO (90nm)
Edge Isolation	Laser isolation	Laser isolation	Laser isolation
Metallization	Standard single screen print High temperature firing	Front: Double-print silver paste; Back: PVD Al (2µm) Low temperature curing	Front: Double-print silver paste; Back: Silver single print Low-temperature curing

3.2 Module processes

The solar glass, encapsulation material, and frame are the same for the standard diffused x-Si module and the heterojunction module. The two differences in the module processes are: 1) the cells are assembled with solder in the mono-Si module, but are assembled with conductive adhesive in the heterojunction module; and 2) the heterojunction module has a different backsheet than the standard module.

4 RESULTS

4.1 Energy Payback Time

The energy payback time, for an illumination of 1700 kWh/m^{2}yr, for the standard mono-crystalline silicon module and for modules composed of the two different types of heterojunction cells are calculated to be 1,45, 1,20 and 1,18 years, respectively. (Figure1)

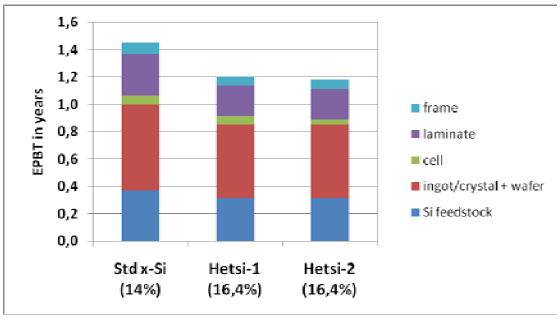

Figure 1: Energy Payback Time, based on an illumination of 1700 kWh/m^2.yr (Southern Europe). The laminate is the module, less the aluminum frame.

4.2 Energy Demand of Cell and Module Processes

The energy contribution (MJ) of Si feedstock, ingot/crystal and wafer components to the cumulative energy demand were assumed identical for all three cell types. This contribution represents 73.1%, 75.5% and 75.1 % of the cumulative energy demand for the processing of standard mono-Si, Hetsi-1 and Hetsi-2 modules (i.e. frame, laminate, cell, ingot and feedstock), respectively.

Figure 2 shows a breakdown of the contributions to the energy demand for cell processing for the conventional mono-crystalline Si solar cell and for the two types of heterojunction cells considered here. A 2% wafer breakage was factored into the cell process, which is ambitious. The heterojunction cells require more wet chemical steps to texture and clean the cells than the standard. The structuring of the standard cell (i.e. diffusing emitter, removing PSG, PECVD of Si_3N_4) requires a slightly larger energy contribution than the structuring of the heterojunctions (PECVD of *i*-,*n*-,*p*- a-Si and TCO depositions). The printing of the heterojunction cell with the ZnO electrode and the full sputtered layer of Al requires a larger contribution, than the open front and rear side printing. The low temperature curing process requires roughly a tenth of the energy of the high temperature firing process. All in all, the energy contributions to make the heterojunction cells are comparable to those needed for the conventional mono-crystalline cell.

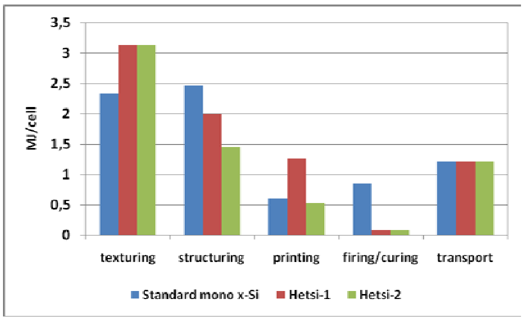

Figure 2: Contribution, in MJ per cell, to the cumulative energy demand of the main cell process steps for the manufacture of the standard mono-crystalline diffused solar cell and the heterojunction cells.

Figure 3 shows the major contributors to the energy demand of the laminate. The heterojunction modules require more aluminum and less PVF than the standard module (i.e the backsheet specified by SOLON) for the conventional module assembly.

The overall conclusion from Figures 2 and 3 is that the heterojunction processing of cells and modules is quite similar to the conventional mono-crystalline cells and modules, in terms of energy demand. The advantage in the heterojunction energy payback time is directly due to the increase in efficiency of these solar cells.

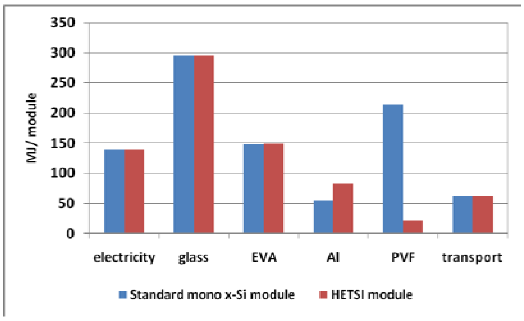

Figure 3: Relative contribution to the cumulative energy demand of the laminate process steps for the manufacture of the standard mono-crystalline silicon solar cell versus the heterojunction modules.

5 GLOBAL WARMING POTENTIAL

Using the method defined by the IPCC (IPCC 2007 GWP 100a), a calculation was performed to determine the quantity, in kg, of CO_2 equivalents produced by the processes and materials involved in the cell and module fabrication of heterojunction versus the standard mono-crystalline solar cells.

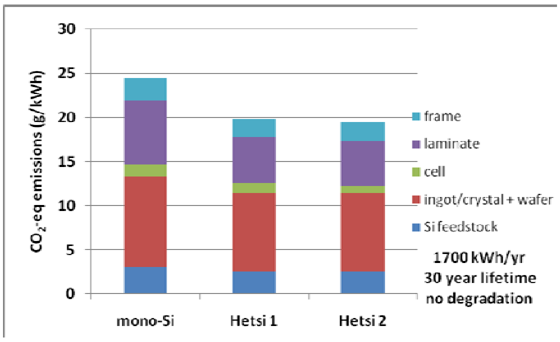

Figure 4: Comparison of CO_2 emission equivalents for mono-Si solar cell and heterojunction module manufacturing (BOS not included)..

The kg of CO_2 equivalent gases produced by the standard and heterojunction cell and module processes are quite similar, when compared per unit module. However, compared in terms of their power output, i.e. Wp/m^2, the heterojunction cells have a more advantageous carbon footprint. Assuming the illumination of southern Europe, (1700 kWh/m^2/yr), a 30 year lifetime and a performance ratio of 75%, the emissions may be calculated in grams of CO_2 equivalents per kWh of operation, as shown in Figure 4. Assuming a degradation rate in the performance of 0.25% per year, the emissions per kWh are slightly higher, as indicated in Table II.

Table II: Indicative Global Warming Potential, in kgs of CO2 equivalents per the Wp of the modules (including frame but not BOS) under study.

	standard mono- Si	Hetsi-1	Hetsi-2
Module *(kg CO_2 equiv/Wp)*	0,932	0,760	0,747
Module, no degradation *(g CO_2 equiv/kWh)*	24,4	19,9	19,5
Module. 0,25% degradation/yr *(g CO_2 equiv/kWh)*	25,2	20,5	20,2

6 DISCUSSION

Because the silicon feedstock, ingot and wafer contribute so substantially to both the energy demand and the emissions, there are significant gains to be had by reducing the thickness of the silicon wafer. Indeed, a 100 µm cell has a 20% less cumulative energy demand than a 180 µm cell. With their low processing temperatures, a-Si:H/c-Si heterojunction solar cell designs can easily employ thinner wafers without the thermal bowing that conventionally (high temperature) processed thin wafers exhibit. In addition, the c-Si material in HJ cells is not doped, which provides better prospects for eventual recycling of the c-silicon wafer.

Among the cell processes, the double silver print required by the HJ cells stands out as a major contributor to the energy demand. Silver is also a significant component of the conductive adhesive used in assembling the module. Because silver is under heavy demand by emerging technologies and markets, the recent trend in solar cell design is to find other metallization options. This holds true also for HJ cells, and the solution of a low resistance low temperature metallization process that does not rely on silver would be a major advance in the development of HJ solar cells.

The HJ cell with two layers of sputtered ITO actually scores better than the one with one sputtered ITO layer and one ZnO layer deposited with CVD. (Figure 2) However, indium is currently a critical material, a by-product of primary ore mining. Its supply has not increased over the last decade despite increased demand from the LCD market. To replace ITO is an imperative in developing sustainable HJ solar cells. Some of the many options include further development of metal oxide layers such as doped ZnO, as well as the newly emerging graphene transparent conducting layers.

7 CONCLUSIONS

The cumulative energy demand and the global warming potential of the ‘standard’ mono-crystalline silicon and the heterojunction require similar amounts of energy and produce similar amounts of CO_2-equivalent of global warming gases per square meter of module. It was assumed that there was no energy or global warming potential impact due to PECVD cleaning with fluorinated gases or ammonia. The higher efficiency of the heterojunction solar cells factors into a more favourable energy payback time, and a lower carbon footprint (per Wp or per kWh).

8 ACKNOWLEDGEMENTS

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9 REFERENCES

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