ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ADVANCED SILICON SOLAR CELL TECHNOLOGIES

E.A. Alsema*, M. J. de Wild-Scholten**

* Department of Science, Technology and Society, Utrecht University, The Netherlands, e.a.alsema@chem.uu.nl,
**Energy research Centre of the Netherlands, ECN Solar Energy, Petten, The Netherlands, m.dewild@ecn.nl

ABSTRACT: An environmental Life Cycle Assessment has been conducted for standard and advanced production technologies for multicrystalline silicon module production and new BOS concepts. It was found that the production route based on Solsilc silicon feedstock and RGS wafer technology can yield a 50% reduction of the environmental impacts in comparison with present-day standard technology. Similar results were obtained for a process using Bayer/Deutsche Solar feedstock material and EFG ribbon technology. New BOS concepts can also help to reduce environmental impacts especially if they allow the use of frameless modules. With such new technologies life-cycle greenhouse gas emissions of PV systems in Southern-Europe can be reduced to about 30 g/kWh and energy pay back time can be as low as 1.2 years.
Keywords: Environmental Effect, Silicon, Manufacturing and Processing

1. INTRODUCTION

Photovoltaic solar energy is always promoted as being a sustainable energy supply technology. At the same time, however, it has to be recognized that present production technologies for solar cell modules have some disadvantages, such as a relatively high energy consumption. This implies that solar cell systems of the present generation have only a limited capability of mitigating greenhouse gas emissions [1]. Also, the recently published ExternE study states that PV electricity has an external cost of 0.6 ct/kWh, as compared to 1-2 ct/kWh for electricity from gas [2].
On the other hand the expectation was always that newer production technologies for PV modules, would help to lower the environmental impacts of PV systems [1].
In order to investigate this further we conducted an environmental Life Cycle Assessment study on advanced production technologies for multicrystalline silicon modules [3]. In this paper we will present the main results of this study.
The study covers new technologies for production of “solar-grade” silicon feedstock, such as “SolSilc” and also the RGS and EFG methods for producing silicon sheet material. Furthermore we have considered new concepts for building integration of PV, such as “PV Wirefree”.

2. METHOD

In our study we used the method of Environmental Life Cycle Assessment (LCA), which comprises a cradle-to-grave analysis of material in- and outputs, energy consumption and environmental emissions of an industrial product. However, the treatment of module waste was not included because of lack of relevant data for recycling processes.
For the final assessment of environmental impacts different methods are in use, but we have chosen for an adapted version of the Baseline-2000 method of the Institute of Environmental Sciences (CML) in Leiden.
We further used the Simapro version 5.1 LCA software in conjunction with the IVAM LCA database.
Data on production processes were based on public literature, internal data from ECN, material lists from manufacturers and own estimates. Because part of our data is proprietary, details for module process routes cannot be disclosed. Energy supply was assumed to be an average of continental W-European supply systems based on the dataset from an ETHZ study [4].

3. INVESTIGATED TECHNOLOGIES

Table 1 below gives an overview of the module technologies that were considered. In the first place there is the “standard” process route, which represents average industrial technology of the year 2000. It employs off-spec silicon from the Siemens silicon production process, standard casting and sawing of 300 μm wafers, and subsequently cell processing and module assembly in a 10-30 MWp/yr module production plant.
Also we looked at two alternative process routes. Both of these employ solar-grade silicon feedstock, produced by the Solsilc respectively the Bayer/ Deutsche Solar processes. Wafers were prepared with either Ribbon-Growth-on-Substrate (RGS) or Edge-defined Film-fed Growth (EFG), both with a 300 μm thickness.

Table I: Silicon solar cell production technologies considered in this study.

	Silicon feedstock	**Wafer/sheet**	**Cell/module production**
Route I: standard	Siemens	Casting + sawing	standard, 10-30 MWp/yr
Route II: advanced	Solsilc	RGS	larger scale, 30-100 MWp/yr
Route III: advanced	Bayer/Deutsche Solar	EFG	

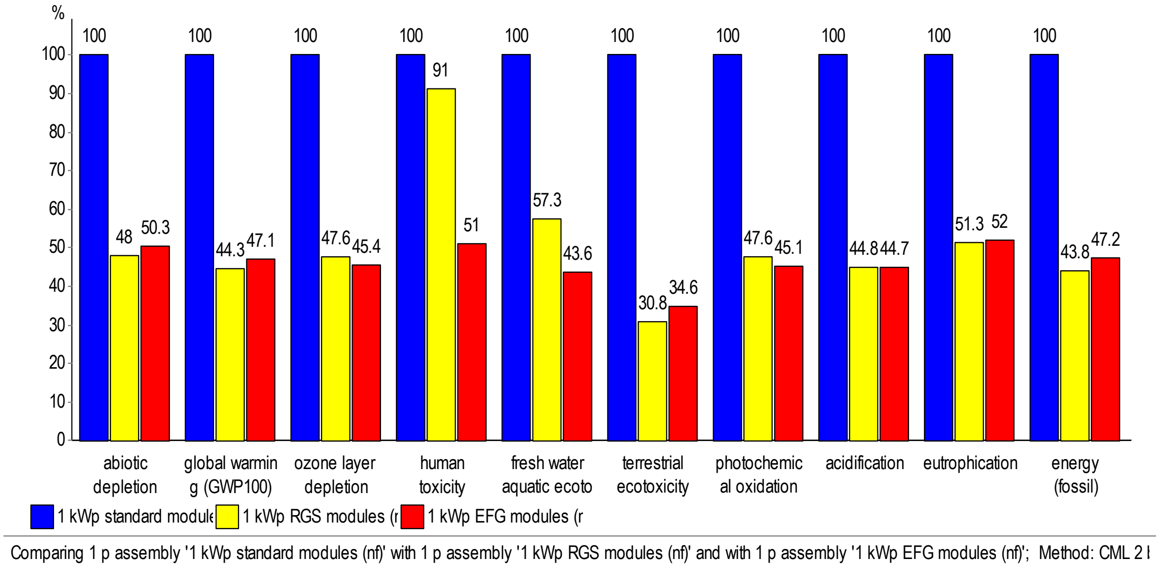

Figure 1*: Comparison of LCA results for 1 kWp of PV modules on the basis of three investigated production technologies, namely standard-2000, Solsilc/RGS and Bayer/EFG.*

Cell and module production were done at a larger production scale (30-100 MWp/yr), thus allowing a 10% reduction of energy and water consumption.
Also a number of alternative BOS concepts and inverter types were included in our analyses. One relatively new concept, TNO/Axys, is already employed in Heerhugowaard in the Netherlands and uses a relatively heavy aluminium array. An alternative concept is the PV Wirefree system [5] in which the array supports have a second function, namely dc-current conduction. Furthermore this concept relies on *frameless* modules. For this system we assumed the use of an OK6 inverter.

4. RESULTS

Figure 1 shows the relative impact scores of the three module technologies for a number of environmental impact categories. Each impact category represents a certain environmental problem area, such as abiotic resource depletion (i.e. depletion of mineral resources[1]), Global Warming, Ozone Layer Depletion, different types of toxicity and acidification. Environmental emissions or other burdens, which have an impact on one of these categories, are weighed and added to determine the impact score of a product. In the figure the highest impact score within a category is always set to 100%, so the other scores are depicted relative to the product with the highest score.
We can see that both advanced technologies do not differ so much from each other but that they do score 50-60% better than standard module technology. This means that both advanced silicon technologies – if they can realise their promises – will yield a very significant improvement of the environmental profile of silicon modules.
When we would compare the impacts of PV modules with the impacts of existing emissions within Europe (figure not shown) we would see the most significant impacts scores for PV modules are those global warming, acidification and energy. These scores are mainly the result of electricity consumption in the module production process. The solar cell preparation including its upstream processes, contributes about 80% to these key impact scores if we consider the standard module. For the Solsilc/RGS or Bayer/EFG modules this contribution has decreased to about 50% (see fig. 2). The improved utilisation of silicon is clearly debit to this result.

If we now consider the impacts of PV systems as a whole (fig. 3) we can see that even with Solsilc/RGS module technology, the modules are still dominant in most impact categories. Inverters do contribute significantly to certain toxicity scores in figure 3 but it has to be noted that these results are rather uncertain. The quite significant contribution of the electronic components in toxicity scores for inverters has a high uncertainty due to lack of LCA data for electronic components.
The PV Wirefree system does offer benefits in comparison with other considered BOS concepts, mainly because it does not need *framed* modules and also because it requires less copper for cabling.

In figure 4 we consider the greenhouse gas mitigation potential of PV technology. Here we depict the GHG emissions of two different PV systems, namely a present-day rooftop system with “standard-technology” framed modules and using the TNO/Axys array supports on the one hand, and an advanced system with Solsilc/RGS modules in a PV Wirefree configuration on the other hand. For comparison we also depict the GHG emissions of a number of conventional and renewable energy technologies.
We can conclude from this figure that a 60% reduction in GHG emissions is possible with advanced PV technologies and that PV systems score significantly better than the best conventional technology (CC gas turbines).

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[1] *In the original CML definition this impact category includes depletion of fossil fuels. However, we have excluded the fossil fuel depletion here and instead created a new impact category “Energy (fossil)”.*

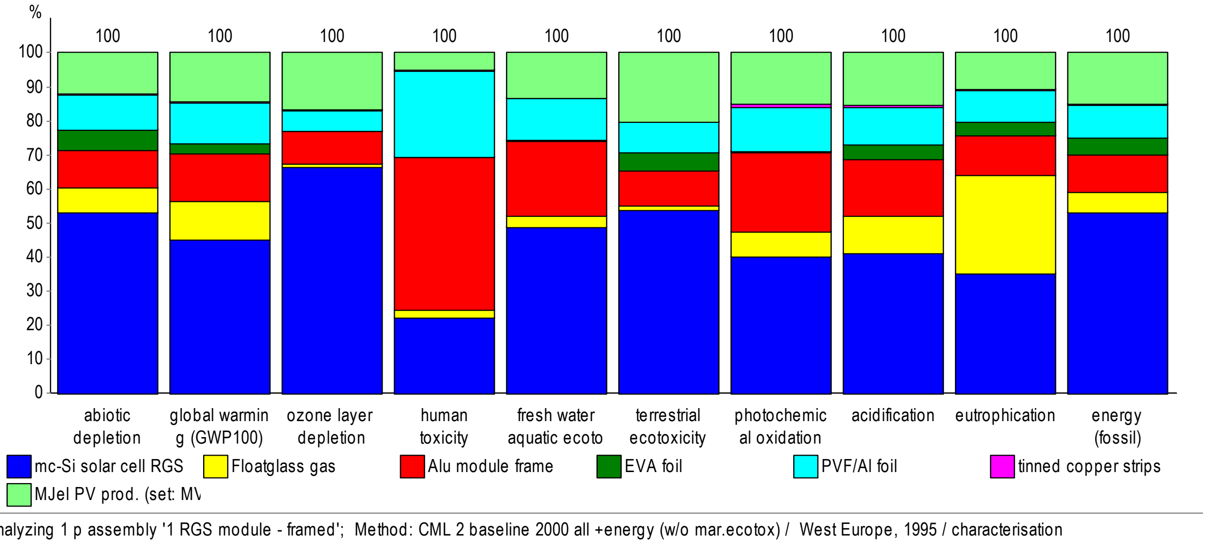

***Figure 2**: Breakdown of the impact scores for 1 RGS module, with relative contributions from the solar cell, cover glass ("float glass"), Aluminium frame, EVA, back foil ("PVF/Al"), connection strips ("tinned copper strips") and finally the electricity consumption for module assembly ("MJel PV production").*

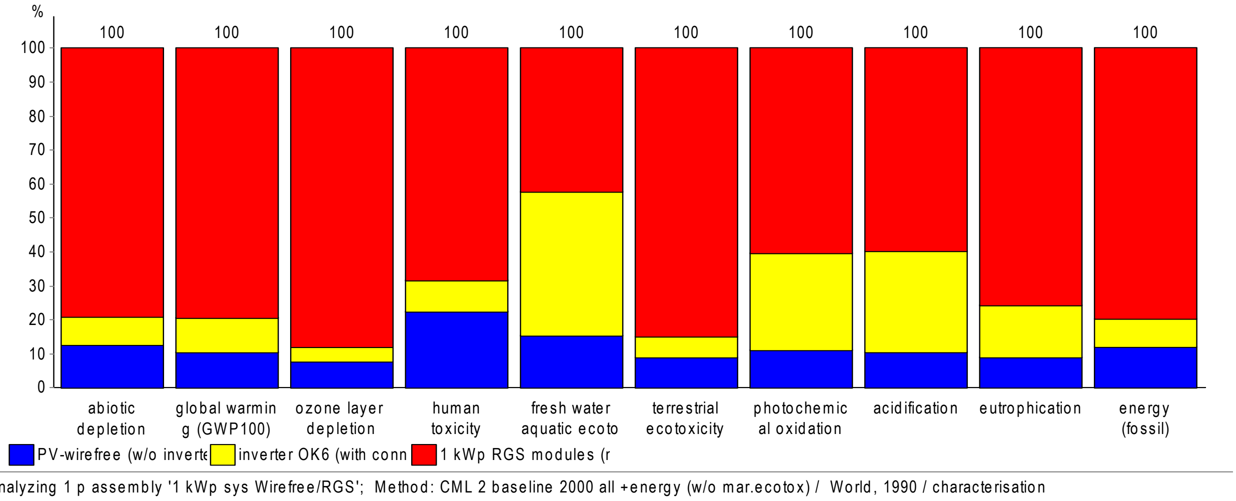

Figure 3: Contribution of system components to environmental impacts for PV Wirefree system with RGS modules

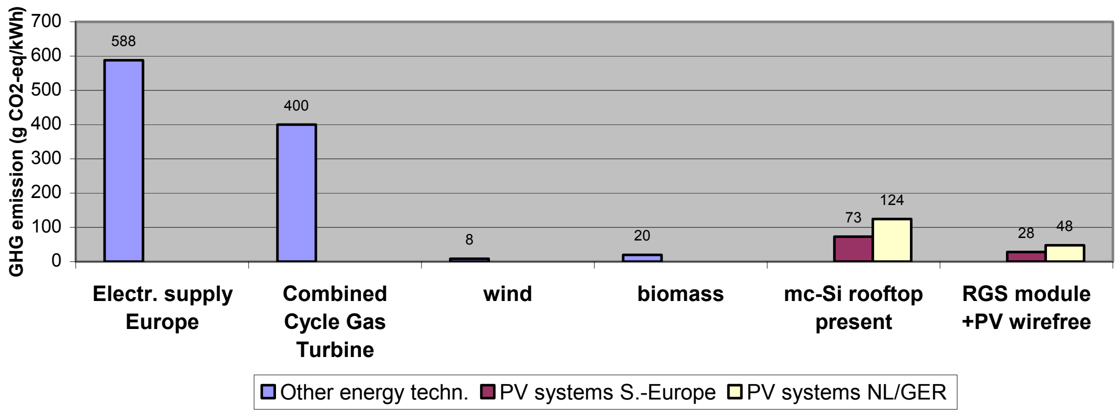

***Figure 4:** Greenhouse gas emissions for a kWh of electricity from different sources. The grid-connected PV systems are located either in Southern-Europe (1275 kWh/kWp/yr output) or in the Netherlands/Germany (750 kWh/kWp/yr).*

Table II: Energy Pay-Back Time for grid-connected PV systems at two different locations

	system output (kWh/kWp/yr)	EPBT (yr)		
		TNO/Axys + standard module	PV Wirefree + standard module	PV Wirefree + RGS module
Netherlands/Germany	750	4.8	4.3	2.0
South-Europe	1275	2.8	2.6	1.2

However it also shows that both PV systems have significantly higher greenhouse gas emissions than wind and biomass technology. This means that despite the potential improvements and notwithstanding the large application potential of PV technology there is still need for further improvement of its environmental profile.

Finally table II shows the Energy Pay-Back times of some considered system concepts at two different locations, one in the Netherlands or (the northern part of) Germany and the other in Southern-Europe. We can conclude that with advanced technologies an EPBT of about two years could be possible.

5. IMPROVEMENT OPTIONS

The following technological improvements were identified that would contribute to a reduction of environmental impacts:

- better utilisation of silicon by more efficient production processes and recycling;
- reduction of silver consumption;
- monitoring of energy and materials input in cell and module production and attention for efficiency of the overhead energy consumption in production plants;
- avoidance of CFC's and PFC's in production processes;
- use of secondary (recycled) materials in BOS components;
- increase of cell conversion efficiency and longer life time of modules and inverters

6. EXTERNAL COSTS OF PV

Recently a discussion has been conducted about the external costs of PV technology as presented in a brochure about the ExternE project [2], which costs (0.6 ct/kWh) were relatively high in comparison with for example wind, gas and nuclear energy. One objection against the ExternE brochure was that the presented results for PV were based on quite old data and therefore were not representative for today's PV technology [6]. A recalculation based on newer studies such as the work presented here is underway but final results will only be presented later this year by the ExternE team. In the meantime it is clear that the *lack of up-to-date, validated LCA data* for PV module production is one of the reasons for the generation and publication of external cost results that do not give a representative and balanced perspective on the external costs of PV in comparison with other technologies. Attempts to remedy this lack of data are now underway but there is still an (understandable) reluctance of industry to share data with LCA researchers. Also the typical data needed, such as energy consumption per process, is often simply not available. A more proactive approach from industry could help to make clear that PV is really the "green" product that it promises to be and also a viable option to mitigate global warming.

6. CONCLUSION

Within (multi)crystalline silicon PV technology good prospects exist to improve the environmental profile of PV systems, possibly by a factor of two. This would improve the position of PV technology in comparison with competing renewable energy options like wind and biomass. Solid guarantees that the outlined improvements will be realised cannot be given because considerable uncertainties still exist with respect to achievable process yields and energy consumption figures.

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