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Environmental impacts of crystalline silicon photovoltaic module production

E.A. Alsema (Utrecht University)
M.J. de Wild-Scholten

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ENVIRONMENTAL IMPACTS OF CRYSTALLINE SILICON PHOTOVOLTAIC MODULE PRODUCTION

Erik A. Alsema[1] and Mariska J. de Wild-Scholten[2]
[1]Copernicus Institute of Sustainable Development and Innovation,
Utrecht University, The Netherlands, e-mail: e.a.alsema@chem.uu.nl;
[2]Energy research Centre of the Netherlands (ECN), Petten, The Netherlands,
e-mail: m.dewild@ecn.nl.

ABSTRACT: Together with a number of PV companies an extensive effort has been made to collect Life Cycle Inventory data that represents the *current status* of production technology for crystalline silicon modules. The new data cover all processes from silicon feedstock production to cell and module manufacturing. All commercial wafer technologies are covered, that is multi- and monocrystalline wafers as well as ribbon technology. The presented data should be representative for the technology status in 2004, although for monocrystalline Si crystallisation further improvement of the data quality is recommended. On the basis of the new data it is shown that c-Si PV systems are in a good position to compete with other energy technologies. Energy Pay-Back Times of 1.7-2.7 yr are found for South-European locations, while life-cycle CO_2 emissions are in the 30-46 g/kWh range. Clear perspectives exist for further improvements of roughly 40-50%.

INTRODUCTION

Reliable data on the environmental impacts of PV module manufacturing have been rather scarce for the last 10-15 years. The only extensive data collection based on production data were published in 1992 [1] and were based on technology from the late 80's. Later work was done to update these data but this was to a large extent based on secondary data sources and estimates [2, 3, 4]. Consequently, life cycle assessment and external cost studies were often based on the old data set that do not really reflect the technological progress made over the past decade.

In a unique collaboration with 11 PV companies from Europe and the USA, we have improved this situation. The contributing companies together cover the complete production chain for crystalline silicon PV modules, from poly-silicon production to module assembly. Also they cover all three major technologies for c-Si, namely multicrystalline, monocrystalline and ribbon silicon wafer technology. This effort was conducted in the framework of the CrystalClear project, a large European Commission co-funded Integrated Project focusing on crystalline silicon technology.

In this paper we present the results of a Life Cycle Assessment study on the basis of these new data.

DATA COLLECTION

The data collection and processing is fully described in a separate paper [5], so we mention here only the main characteristics. All data were collected in the period September 2004 –

November 2005 and are representative for the technology status in 2004. Cell production data for the considered facilities totalled about 160 MWp in 2004, all of them located in Europe. Also for multi-Si wafer production we cover a sizable share of the European market, while for ribbon technology we probably cover *all* production capacity in the world. For mono-Si crystallization data quality and market coverage is less good, it is mainly based on literature data from facilities in the USA and Western-Europe. All-in-all we consider our data set as a major improvement over previous work because: 1) it is based to a large extent on measured data from several sources and 2) it represents the actual technology status for 2004.

TECHNOLOGY ASSUMPTIONS, LCA METHOD AND BACKGROUND DATA

With regard to wafer dimensions we assumed a 125x125 mm as the standard size for all wafer technologies (including ribbon). Where actual cell or wafer dimensions differed from this standard we scaled energy and material consumption correspondingly. Although 150x150 mm wafer technology is growing fast in market share, this up-scaling in wafer area will have only minor effects on LCA results in terms of impacts per m^2 module or per kWp power. Wafer thickness was in the range of 270-300 μm for mono- and multi-Si wafers and 300-330 μm for ribbon wafers.

We considered only one standard module type with 72 cells (1.25 m^2 module area), with glass/EVA/Tedlar lamination. Glass thickness was set at 3.6 mm. We looked at both laminates (i.e., unframed modules) and framed modules, which have an aluminium frame of 3.8 kg. Module efficiencies were roughly based on commercially available modules of each specific technology (Table I). Module life time was assumed to be 30 years; the life time of electronic components of the PV systems (inverter) was set at 15 years.

Table I: Assumed module efficiencies per technology (measured on full-area, without frame).

Ribbon Si	Multi-Si	Mono-Si
11.5%	13.2%	14%

The LCA analyses were performed with the Simapro software (version 6.04) with the Ecoinvent 2000 database (version 1.2) for background processes (i.e. production of electricity, glass, metals, chemicals).

Because we focus mainly on module production our functional unit is in principle 1 kWp of modules. Since most energy and material inputs are directly related to the cell or module area, while the specific power rating of modules (in Wp/m^2) may vary between manufacturers, we will often show results per m^2 module area. Furthermore, comparisons with other energy technologies will be done with 1 kWh of generated electricity as the functional unit.

Impact assessments were made on the basis of the CML 2000 baseline method[1], as implemented in Simapro, with normalisation factors for West Europe 1995. Greenhouse gas emissions are evaluated with IPCC 2001 data for a timeframe of 100 years, while the Cumulative Energy Demand (CED) is calculated by the method described in Ecoinvent 1.01, where we have

[1] Some impact categories of the original CML method (all toxicity impacts) were omitted because there are still too much scientific uncertainties with regard to the impact evaluation in these categories.

summed all fossil, nuclear, hydro and renewable energy demand into one single CED value.

Most of the background data for our LCA, such as inventories for production of glass, chemicals and metals were based on the Ecoinvent database version 1.2 [6], with own additions for PV-specific materials. The production of metallurgical-grade silicon was also modelled on the basis of Ecoinvent data. The scope of our analysis comprises all production processes for manufacturing of crystalline silicon solar cell modules, from silica mining up to module assembly. End-of-life disposal of modules is not included here, but a separate paper at this conference presents an LCA study of a pilot-scale process for module recycling [7]. Environmental impacts during the use phase of a PV system are generally negligible, the replacement of electronic components (inverter) after 15 years is accounted for by including two inverters in the system.

For all manufacturing processes, *except the production of purified polycrystalline silicon ("poly-Si"),* we assumed the average electricity supply system for the Western-European continent (UCTE region), at medium voltage level, as given by the Ecoinvent database. This system has an overall conversion efficiency of 31% and a greenhouse gas emission of 0.48 kg CO_2-eq/kWh. For the poly-silicon production the electricity supply was specifically adapted to the two considered facilities, and based on respectively 100% hydropower and a mixture of hydropower and combined cycle gas turbine generation.

LCA RESULTS FOR PV MODULES

First we will give LCA results for modules, identify the most significant impacts and analyse the contributions from the specific process steps and input materials.

Figure 1 gives the overall characterised results for the three module types (functional unit 1 kWp). We see that in all impact categories the monocrystalline technology has the highest impacts score, while ribbon modules have the lowest impacts. We will see later that this is mainly related to the energy demand in the production processes.

Figure 2 shows the same results but now normalised by the total impact scores of all economic activities in W. Europe in 1995, thus showing the relative importance of the different impacts from the PV modules. We see that abiotic resource depletion, global warming and acidification are the most significant impacts, while ozon layer depletion gives a very small normalised impact score. It can be shown that the first three impacts are all dominated by emissions from energy conversion processes: the abiotic depletion because this includes the depletion of fossil fuels, the global warming and acidification because of the emissions from fuel combustion. This strong link with energy demand means that if we are able to reduce energy consumption we will also reduce the main environmental impact scores. Because energy input is an important factor we will now analyse this aspect in more detail.

Figure 3 shows the Cumulative Energy Demand (CED) for the three module types, expressed in MJ of primary energy (MJ_p) per m^2 of module area[2,3]. Note that this energy value comprises both process energy and energy embedded in consumed materials. The relative magnitude of the

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[2] *Results are here depicted per unit area because all major (energy) inputs are area-related.*

[3] *Differences with previously published, preliminary results for energy input are mainly due to changed assumptions with regard to the electricity supply mix for poly-Si production (less hydro, more gas) and a heavier module frame.*

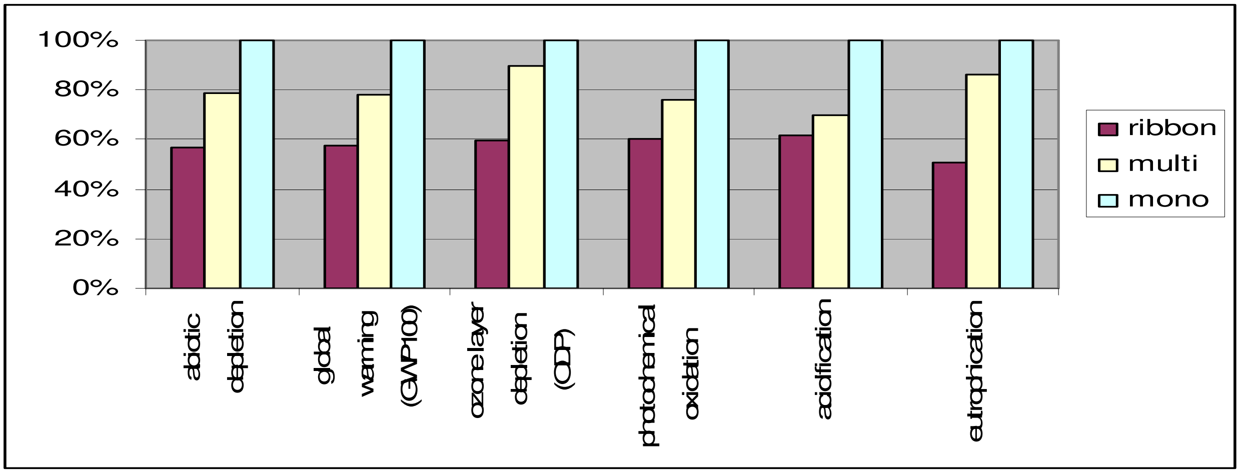

Figure 1: LCA comparison of the three types of crystaline silicon modules (characterised results for 1 kWp of module capacity; adapted CML 2000 Baseline method). The highest impact in each category is scaled to 100%.

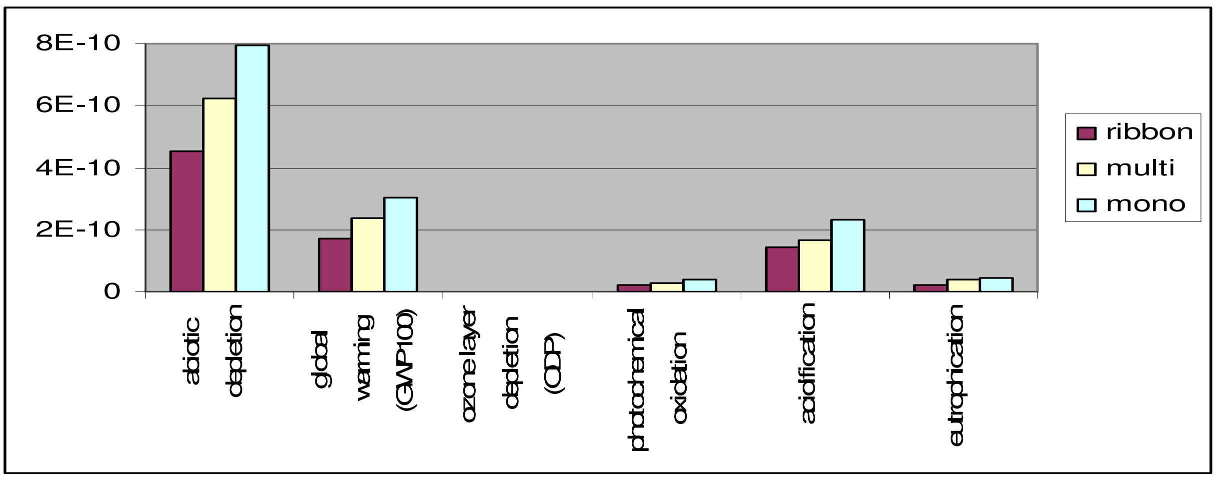

Figure 2: Normalised LCA results for the three module types (normalization: W.-Europe 1995). The Y-axis gives the impacts of our products relative to the impact of *all economic activities* in W.-Europe in 1995.

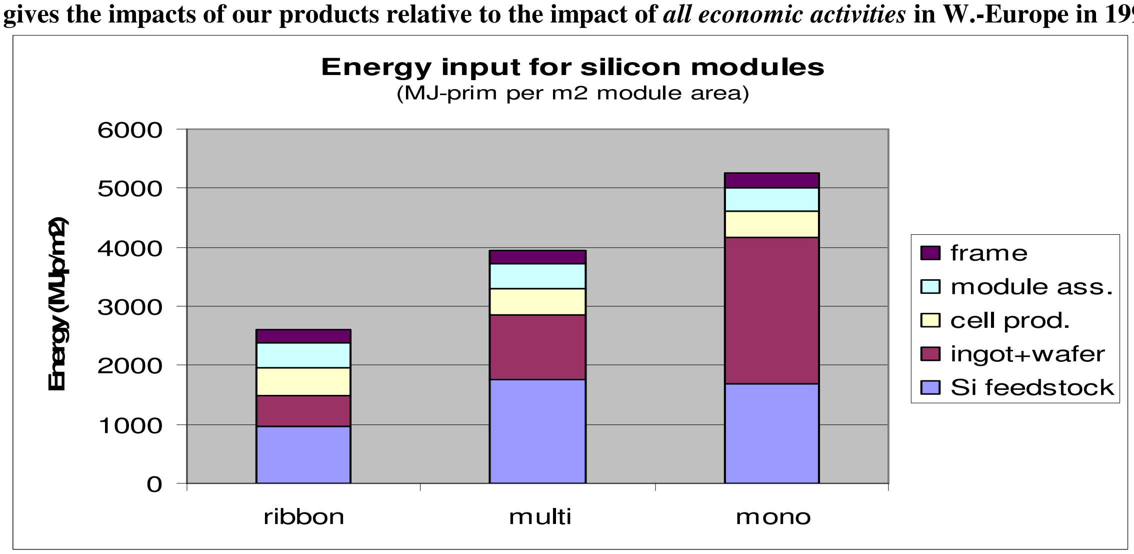

Figure 3: Energy input for crystalline silicon modules, in MJ of primary energy per m^2 of module area, with the contributions of consecutive process steps.

cumulative energy demand for the three module types is clearly similar to the relative impact scores for abiotic depletion, global warming and acidification in figure 1, a similarity which supports our assertion that these impacts are dominated by energy conversion processes.

Contributions from the different process steps are also shown in figure 3 and we can see that poly-silicon production has a large contribution, but also crystallization and wafering, especially for mono-Si material. As mentioned above, however, data for this latter process step is less good as we would like. The energy input for ribbon modules is the lowest, which is mainly due to reduced poly-Si consumption (no silicon loss from wafer sawing) and also because of lower energy requirements in the crystallization & wafering step. The processes of cell and module production, which are the same for all three technologies, have less important contributions to the cumulative energy demand.

Figure 4 and 5 give a different break-down of the energy input for respectively a multi-Si wafer and a module of the same type. Most notable in Figure 4 is that for wafer production not only the poly-Si material has an important contribution, but also the silicon carbide and other materials that are used in wafer cutting. This share will grow when wafer thickness is further reduced. In Figure 5 we can see that apart from the wafer itself the encapsulation materials (glass,

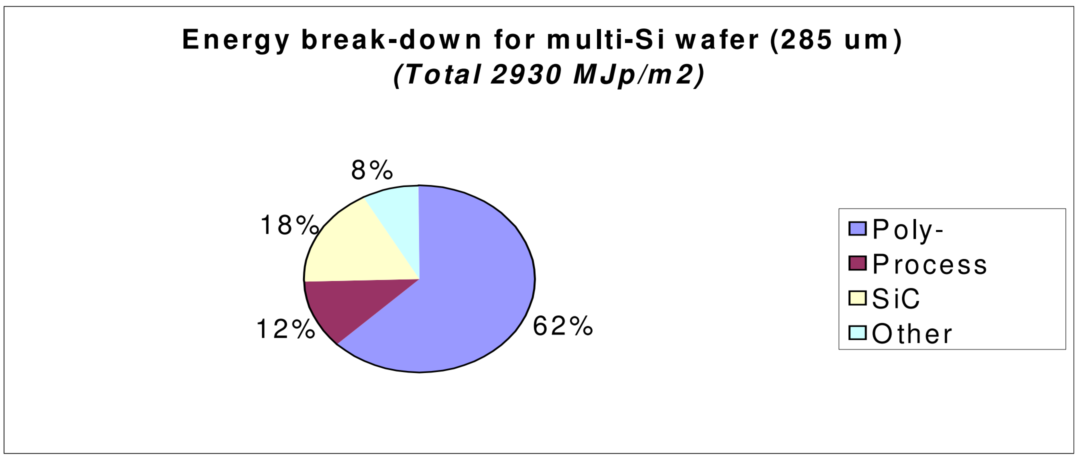

Figure 4: Energy input breakdown by source for a multi-Si wafer (125x125 cm^2, 285 um thick)

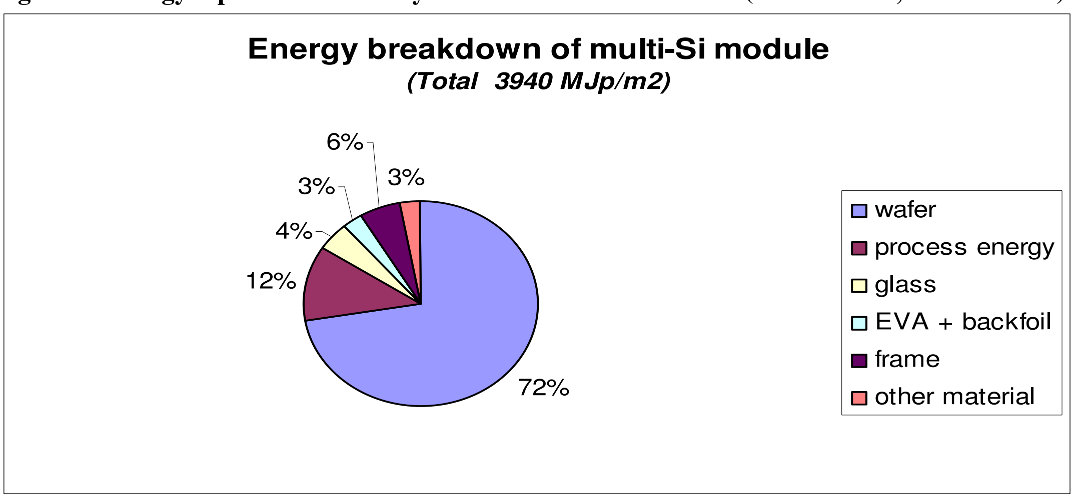

Figure 5: Energy input breakdown by source for a multi-Si module (72 cells, 165 Wp). Note that production of 1 m^2 of module area uses only 0.92 m^2 of wafer area as input.

EVA, back foil) and the frame also have a significant share in the energy requirement of a module.

By applying the module efficiency assumptions of table I and by converting the MJ_p to kWh_e, we calculated the following module energy input values expressed in kWh_e per kWp[4]: 1950 kWh_e/kWp for ribbon, 2570 for multi- and 3230 for monocrystalline silicon.

EVALUATION OF PV SYSTEMS

We will now look at complete PV systems and evaluate these in terms of their Energy Pay-Back Time (EPBT) and life cycle CO_2 emissions.

For the evaluation of the Energy Pay-Back Time of a PV system we assume that the modules are installed in a grid-connected roof-top system with a Performance Ratio of 0.75[5]. Under a 1700 kWh/m^2/yr irradiation (Southern-Europe) the system can thus generate 1275 kWh/kWp/yr of electricity. If this electricity is fed back to the same electricity supply system that was used for manufacturing (this is not necessarily the case), then we can save 14780 MJ of primary energy per kWp per year. Further assumptions for the energy input of the BOS components are taken from a previous study [3] and summarized in table II.

Table II: Energy and CO_2 data of BOS components used for EPBT and CO_2 emission evaluations on a system level [3]. Inverter data includes one replacement half-way the system life.

	Energy input	CO_2-eq emission
Array support +cabling	100 MJ_p/m^2	6.1 kg/m^2
Inverter	1930 MJ_p/kWp	125 kg/kWp

Figure 6 shows the resulting Energy Pay-Back Times in years. We can see that EPBT's are in the range of 1.7-2.7 years for a South-European location, while for Middle-Europe (irradiation 1000 kWh/m^2/yr) locations we obtain higher EPBT values in the 2.8-4.6 year range.

From Figure 6 it is clear that the laminate (unframed module) dominates the energy pay back results, while the Balance-of-System has a relatively small contribution. The contribution of the module is shown separately because its contribution relatively large and sometimes systems are built with frameless modules (laminates) too.

Also remark that the difference between ribbon, multi- and mono-Si has decreased in comparison with figure 1. This is of course due to the differences in module efficiency, with ribbon having somewhat lower and mono-Si a bit higher value (cf. Table I).

Based on our LCA results regarding greenhouse gas (GHG) emissions for module manufacturing we can in a similar way as above evaluate the life-cycle GHG emissions of our PV system, expressed in kg CO_2-eq per kWh. For this evaluation we further use the BOS data in table II and assume a 30 year system life time.

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[4] *This unit is more commonly used within the PV community because it allows easy comparison of energy input (as electricity) and energy output; implicitly it converts all material energy demands to an electricity equivalent. For the considered electricity system 1 kWh_e is equivalent to 11.6 MJ_p.*

[5] *This means that a 1 kWp system under an irradiation H (in kWh/m^2/yr) will generate $E= PR*H$ of electricity (in kWh/yr). Note that this PR value might be somewhat conservative, especially for systems in Southern-Europe*

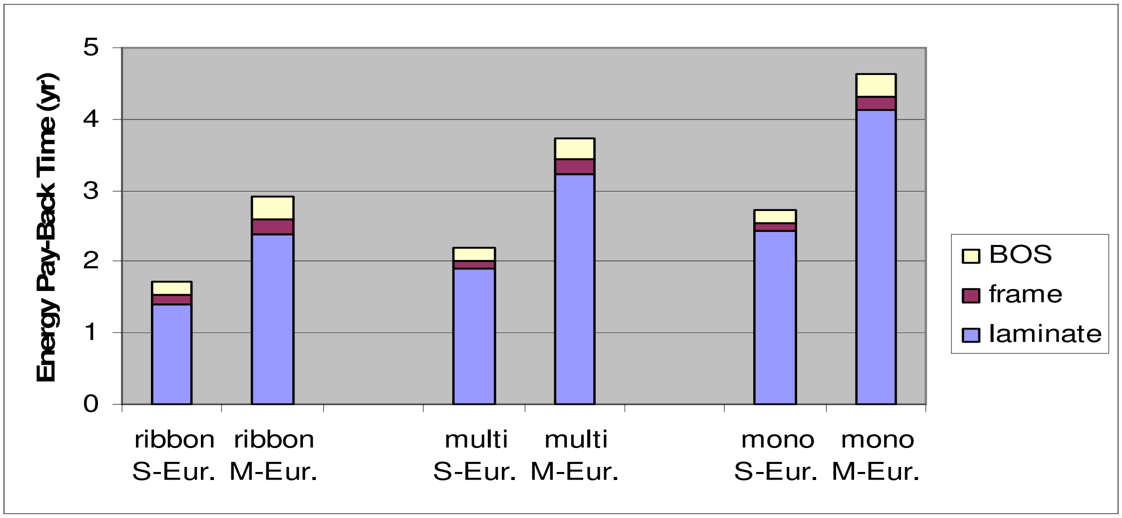

Figure 6: Energy Pay-Back Time (in yr) for a grid-connected PV-system under an irradiation of 1700 kWh/m^2/yr (Southern-Europe) respectively 1000 kWh/m^2/yr (Middle-Europe).

Figure 7 shows the results of this exercise, and compares today's PV systems with a number of other energy supply options. We can see that PV with a GHG emission of 30-45 g CO_2-eq, performs quite well in comparison with fossil-fuel-based technologies, but less so in comparison with wind and nuclear technology.

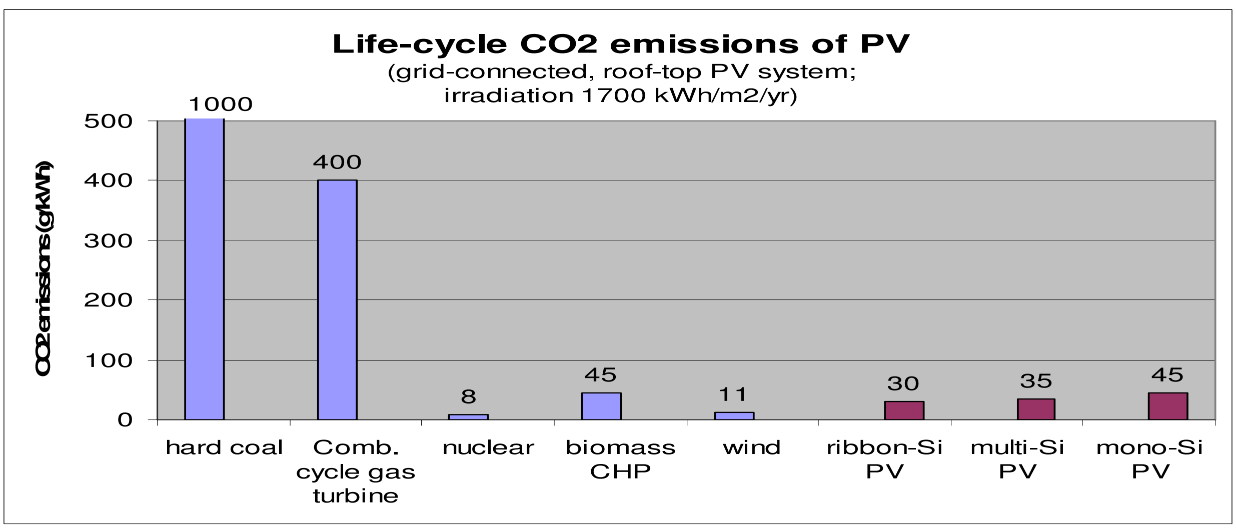

Figure 7: Greenhouse gas emissions of PV systems based on three silicon technologies, compared to a number of other energy technologies. The PV systems are installed on a roof-top in S.-Europe (irradiation 1700 kWh/m^2/yr) and have a 30 year life time. N.B. The emission from a coal-fired power plant (1000 g/kWh) exceeds the Y-axis maximum ! (Sources: Coal, CC gas, nuclear, biomass and wind data derived from Ecoinvent database [6])

FUTURE DEVELOPMENTS

It is also interesting to look what developments may be possible in the future. In poly-silicon feedstock production the application of Fluidized Bed Reactors (FBR) for silicon deposition could significantly reduce electricity consumption. Also we have clear indications that construction of new facilities for multi-Si casting and wafering could reduce energy consumption for this process significantly too. Within the Crystal Clear project it is furthermore an aim to reduce wafer thickness to 150 μm. For cell and module manufacturing reduction options are less clear however, and energy input may even increase for example by introduction of clean room environments. We do assume however that module efficiency can be increased significantly without increasing process energy (or material) consumption. Finally we assume that frameless modules become the standard technology.

Table III gives an overview of the improvements that we consider feasible for ribbon and multi-Si technology within the next 5-8 years. We refrained from an analysis of mono-Si technology because our data basis for *current* mono-Si technology still has too much uncertainty.

Table III: Assumptions for future multi-Si and ribbon technology

	Multi-Si	Ribbon-Si
Si Feedstock	Fluidized Bed Reactor deposition of "Solar Grade" Silicon	
Crystallisation	Best Available Technology 2004	Standard Technology 2004
Wafer thickness	285 -> 150 um	300 -> 200 um
Module efficiency	13.2 -> 16%	11.5 -> 15 %
Module assembly	Frameless module	Frameless module

When we analyse the production of such modules we find that significant reductions in EPBT are possible, to about 1 year for a South-European location (Figure 8). The introduction of FBR technology for silicon feedstock production plays an important role in this improvement because it can reduce the electricity consumption for poly-silicon deposition by at least 70%.

Under the same assumptions life cycle CO_2 emissions could drop to 17 and 20 g/kWh respectively for ribbon and multi-c-Si technologies, bringing them nicely in the same range as other renewable energy technologies.

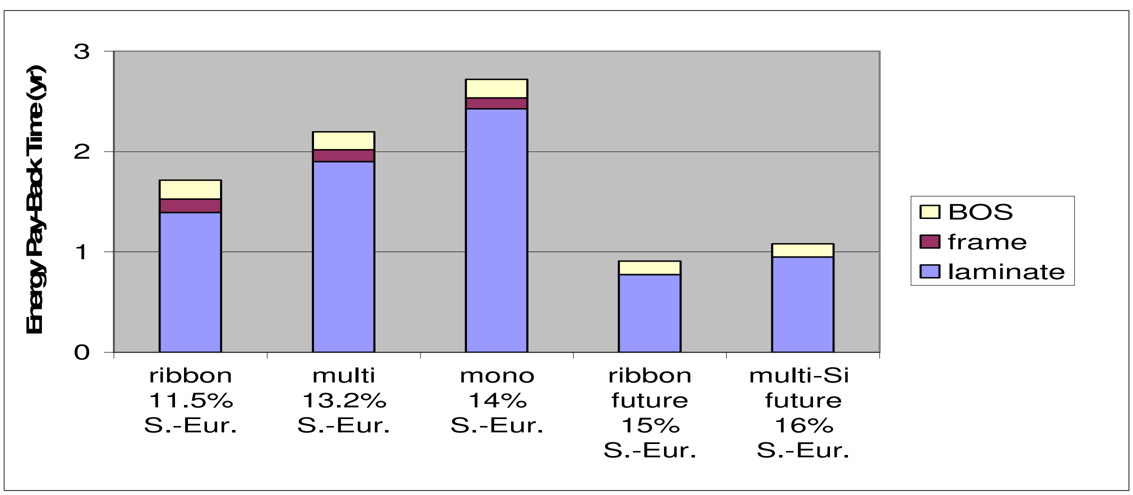

Figure 8: Energy Pay-Back Time for future multi-Si and ribbon technology (two bars at the right), compared with today's status. The numbers below the X-axis give the respective module efficiencies.

There are also definitive points of attention for the future. If the use of fluorinated gases for dry etching increases it is very important that proper emission abatement equipment is installed. At this moment CF_4 is already used in some production facilities and not always abatement equipment is in place. For a CF_4 consumption of 40 kg per MWp which is emitted unabated, the total greenhouse gas emission of modules may increase by 20%!

CONCLUSIONS

Together with a number of PV companies an extensive effort has been made to collect Life Cycle Inventory data that represents the *current status* of production technology for crystalline silicon modules. On the basis of these new data it is shown that PV systems are in a good position to compete with other energy technologies. Energy Pay-Back Times of 1.7-2.7 yr are found for South-European locations, while life-cycle CO_2 emission is in the 30-45 g/kWh range. Clear perspectives exist for further improving these estimates in the near-term by about 40-50%. On the other hand substantial increases in greenhouse gas emission will occur if consumption of fluorinated gases increases and these are emitted unabated.

Further improvements in data quality are needed in the field of mono-crystalline silicon ingot growing.

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REFERENCES

1. Hagedorn, G. and E. Hellriegel, Umwelrelevante Masseneinträge bei der Herstellung verschiedener Solarzellentypen – Endbericht, Forschungstelle für Energiewirtschaft, München, Germany, 1992.
2. Alsema, E.A., Energy Pay-Back Time and CO_2 emissions of PV Systems. Progress In Photovoltaics: Research and Applications, 2000. 8(1): p. 17-25.
3. Alsema, E.A. and M.J. de Wild-Scholten. Environmental Life Cycle Assessment of Advanced Silicon Solar Cell Technologies, 19th European Photovoltaic Solar Energy Conference, 2004, Paris.
4. Jungbluth,N. (2005): Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database; *Progress in Photovoltaics: Research and Applications* **13** (**5**): 429-446
5. de Wild-Scholten, M.J. and E.A. Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production, Proceedings of MRS Fall 2005 Meeting, Symposium G, Boston, MS, Nov-Dec 2005.
6. Ecoinvent database version 1.2. See http://www.ecoinvent.ch/
7. Müller, A., K. Wambach and E.A. Alsema, Life Cycle Analysis of Solar Module Recycling Process, Proceedings of MRS Fall 2005 Meeting, Symposium G, Boston, MS, Nov-Dec 2005