THE REAL ENVIRONMENTAL IMPACTS OF CRYSTALLINE SILICON PV MODULES: AN ANALYSIS BASED ON UP-TO-DATE MANUFACTURERS DATA

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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 covers 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 PV systems on the basis of c-Si technology are in a good position to compete with other energy technologies. Energy Pay-Back Times of 1.5-2.5 yr are found for South-European locations, while life-cycle CO_2 emission is in the 25-40 g/kWh range. Clear perspectives exist for further improvements with roughly 25%.

Keywords: Environmental Effect, Life Cycle Assessment, c-Si

1 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 was published in 1992 [1] and was 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 older data set that does not really reflect the technological progress made over the past decade.

In a unique collaboration with nine PV companies from Europe and the USA, we have made a start to improve 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.

As a first step we have prepared together with the industrial partners, an up-to-date set of life-cycle inventory data based on real measured data from production lines. Based on these data a Life Cycle Assessment study has been performed. Preliminary results of this work-in-progress are being presented below.

2 DATA COLLECTION AND PROCESSING

As mentioned we were able to obtain the cooperation of nine PV companies which together cover the entire production chain for silicon PV modules. As material and energy consumption data are mostly considered as confidential information by companies this took quite some time. Also many companies had to make a special effort to collect the requested data.

Because one of our aims is to prepare a *publishable* set of Life Cycle Inventory data (i.e. data on material and energy inputs, as well as emissions per process step) we tried to get at least three data suppliers for each process step and process technology (e.g. mono vs. multi-Si). In this way we could generate average LCI data without disclosing proprietary information. This goal was realized to a large extent but in some cells of the process/technology matrix (table I) the data collection took more time or the process was less well covered so that we had to make use of existing data from literature. Also we needed to aggregate the process data into 4 main process steps, see table I.

For silicon feedstock production we had one set of new data, which we aggregated with existing data from literature [2, 4]. For crystallization and cutting of multi-Si wafers we had data sets from three facilities, and the same goes for ribbon growing. Among the ribbon growing technologies, though, there is one process (RGS), which is only in a pilot stage. For the purpose of data aggregation we considered this as a commercial–scale operation. Nonetheless, the aggregated ribbon process data can be considered as representative for today's technology.

Table I: Overview of data sources used for the analyses in this paper. "New data" refers to manufacturers data collected over the past year within the CrystalClear project, "existing data" comes from literature or from the Ecoinvent LCA database [4].

Technology/ Process step	Multi-Si	Mono-Si	Ribbon Si
Si feedstock	New data + existing (literature)		
Crystallization + wafering	New data	Existing data + updates	New data
Cell processing	New data		
Module assembly	Existing data + updates		

For mono-crystalline silicon ingot growing and cutting there is unfortunately quite some uncertainty in the data. We did use data for ingot growing as measured some five years ago [5], updated with information on some subsequent process improvements [6]. This was aggregated with data from literature [4]. Because of the observed discrepancies and uncertainties and in view of relative importance of this process step we would like to improve on the data accuracy and representativeness.

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With regard to cell processing we did not distinguish between multi-, mono- and ribbon technology because the observed differences were small (in terms of environmental impacts). Here we obtained data from 5 different sources.
For module assembly, finally, we had only a few new data, but earlier published values for this process from Ecoinvent [4] we consider to be reasonably reliable.

All data were collected in the period September 2004 – May 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. For mono-Si crystallization market coverage is less good, for example the sizable production by Eastern European and (former) Russian suppliers is not covered.
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 more than one source and 2) it represents the actual technology status for 2004!

3. ASSUMPTIONS 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 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 (=unframed modules) and framed modules, which have an aluminium frame of 2.4 kg. Module efficiencies were roughly based on commercially available modules of each specific technology (table II).

Table II: Assumed module efficiencies per technology.

Ribbon Si	Multi-Si	Mono-Si
11.5%	13.2%	13.7%

Most of the background data for our LCA, such as inventories for production of glass, chemicals, metals etcetera were based on the Ecoinvent database version 1.1 [4], with own additions for PV-specific materials. For all manufacturing processes, *except poly-Si production,* 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 100% hydropower respectively a mixture of hydropower and combined cycle gas turbine generation.

4 RESULTS

First of all we want to emphasize that the results presented below are *preliminary* and may change slightly when we obtain additional manufacturing data and further improve our background data. Major changes are not expected, though.
We focus on energy requirements and Energy Pay-Back Time first, because PV is an energy technology and because energy consumption is the major contributor to the environmental impacts of crystalline silicon PV. Figure 1 shows the energy requirements for the three module types, expressed in MJ of primary energy[1] (MJ_p) per m^2 of module area[2]. Contributions from the different process steps are shown; note that this comprises both process energy and energy embedded in consumed materials. 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 process step is less good as we would like.
As might be expected the energy input for ribbon modules is the lowest, due to reduced poly-Si consumption and also because of lower energy requirements in the crystallization & wafering step. Cell and module production have less important contributions, where the latter is dominated by energy embedded in materials (glass, EVA).

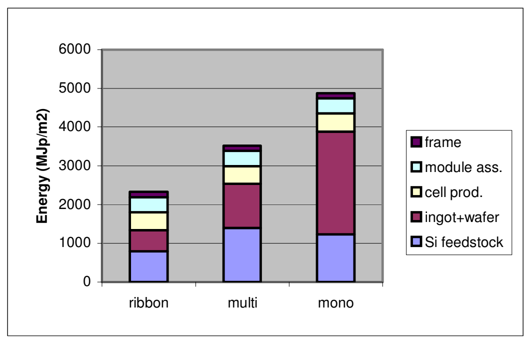

Figure 1: Energy input for crystalline silicon modules, in MJ of primary energy per m^2 of module area, with the contributions of specific process steps.

If we now apply the module efficiency assumptions of table I and convert the MJ_p to kWh_e, we easily calculate the following module energy input values expressed in kWh per kWp: 1750 for ribbon, 2300 for multi- and 3070 for monocrystalline silicon.

Also we can evaluate the Energy Pay-Back Time of PV systems with these module types. For this purpose we consider grid-connected roof-top systems with a Performance Ratio of 0.75. Under a 1700 kWh/m^2/yr irradiation (Southern-Europe) the system can then 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

[1] *For the considered electricity system 1 kWh_e is equivalent to 11.6 MJ_p.*
[2] Results are first evaluated per unit area because major (energy) inputs are area-related.

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 III.

Table III: Energy and CO_2 data of BOS components used for EPBT and CO_2 emission evaluations on a system level [3].

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

Figure 2 shows the resulting Energy Pay-Back Times in years. We can see that pay back times are in the range of 1.5-2.5 years for a South-European location, for Middle-Europe (irradiation 1000 $kWh/m^2/yr$) we obtain higher EPBT values in the 2.6-4.4 year range.
From figure 2 it is also clear that the laminate (unframed module) dominates. 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.

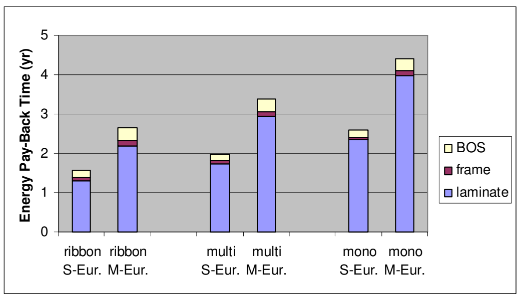

Figure 2: Energy Pay-Back Time (in yr) for a grid-connected PV-system under an irradiation of 1700 $kWh/m^2/yr$ (Southern-Europe) respectively 1000 $kWh/m^2/yr$ (Middle-Europe).

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 III and assume a 30 year system life time.
Figure 3 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 26-40 g CO_2, performs quite well in comparison with fossil fuel-based technologies, but less so in comparison with other renewable energy technologies.

More extensive LCA analyses are underway with one result being shown in Figure 4. This figure shows that if we compare environmental impacts between module types, the comparative results for most impact categories roughly follow the energy input results given in figure 1. The reason for this is that energy consumption is a major contributor in these impact categories (e.g. global warming, ozone layer depletion, acidification). Impact categories which are less dominated by energy consumption are resource depletion (97% from silver consumption!) and human toxicity.

5. PAST AND FUTURE DEVELOPMENTS

It is interesting to compare these results with analyses from some years back. Figure 5 shows the present results for modules next to our estimates for the technology in 1999 [2]. We can see that energy input per unit area has been reduced by 25%, largely because of reduced silicon feedstock energy. This is primarily due to reduced wafer thickness (from 350 µm to 270-300 µm). For the rest the 1999 estimates were fairly accurate, the framing contribution having dropped because of increased module area.
Because our 1999 module efficiency assumptions were almost the same as they are now (too optimistic in '99?), the change in Energy Pay-Back Time is roughly the same as for module energy input.

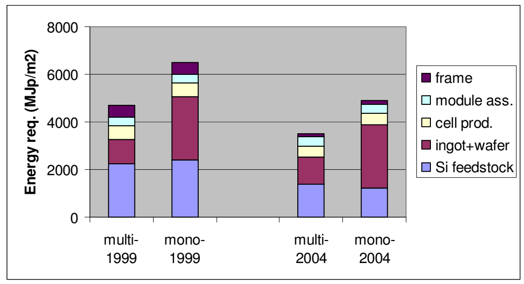

Figure 5: Comparison of present results (2004) on energy input of crystalline Si module with own estimates from 1999 [2]. (Ribbon data were not available in '99.)

It is also interesting to look what developments may be possible in the future. In poly-silicon production the application of Fluidized Bed Reactors 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.
A very rough assessment indicates that the mentioned improvements in poly-Si and crystallisation, together with reduced wafer thickness might reduce the energy input of multi-Si wafers by another 25%. The overall environmental profile of PV systems would clearly profit substantially from these developments.
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%!

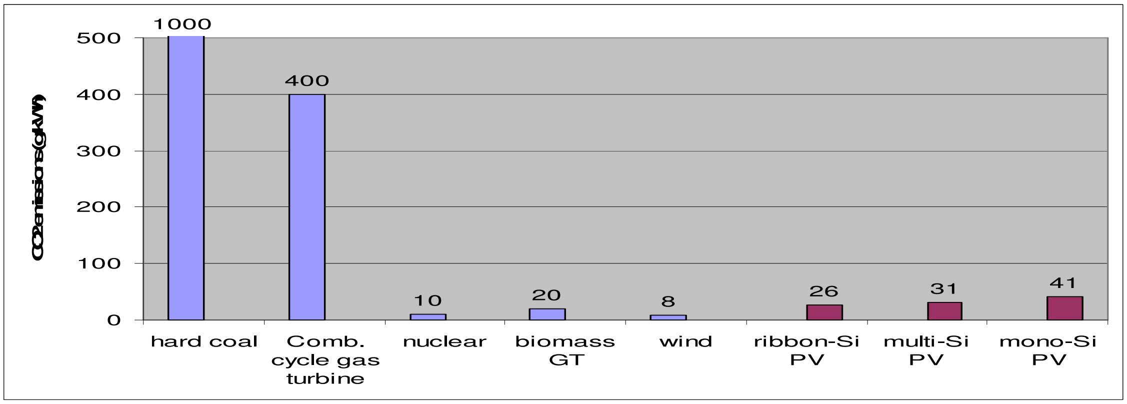

Figure 3: Life-cycle greenhouse gas emissions for grid-connected PV systems, under 1700 kWh/m^2/yr irradiation. For comparison a number of other energy options [2] are also shown .

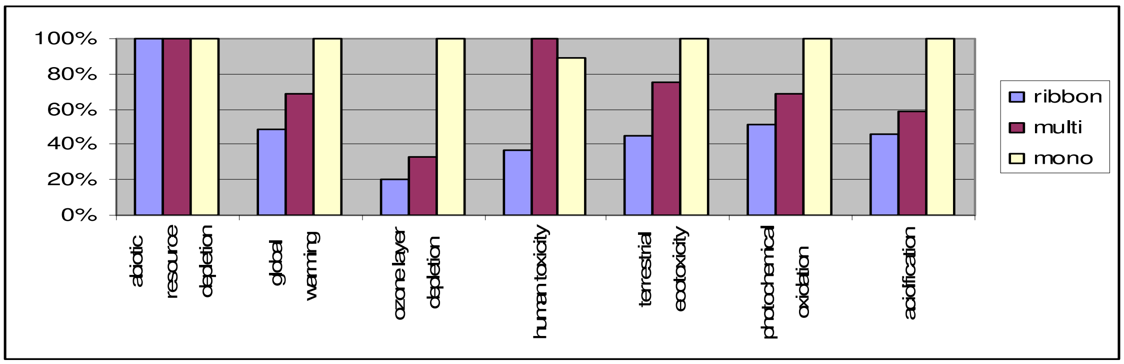

Figure 4: LCA results for the three module types. The characterisation results show the relative magnitude of environmental impacts between the module types for certain impact categories (e.g. global warming, ozone layer depletion).

6. 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 this new data it is shown that PV systems on the basis of c-Si technology are in a good position to compete with other energy technologies. Energy Pay-Back Times of 1.5-2.5 yr are found for South-European locations, while life-cycle CO_2 emission is in the 25-40 g/kWh range. Clear perspectives exist for further improvements with roughly 25%. 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 recommended in the field of mono-crystalline silicon ingot growing.

7. ACKNOWLEDGEMENTS

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