REDUCTION OF THE ENVIRONMENTAL IMPACTS IN CRYSTALLINE SILICON MODULE MANUFACTURING

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ABSTRACT: In this paper we review the most important options to reduce environmental impacts of crystalline silicon modules. We investigate which are the main barriers for implementation of the measure. Finally we review which measures to reduce environmental impacts could also lead to a cost reduction. Reduction of silicon consumption is a measure which will significantly reduce environmental impacts and at the same time has a cost reduction potential. Silicon feedstock processes with lower energy consumption such as Fluidized Bed Reactor technology, also have a large impact reduction potential. Together these two options can reduce the Energy Pay-Back Time of a PV installation (in South-Europe) to values well below 1 year. Other improvement options are identified in crystal growing and cell and module manufacturing.

A number of options is likely to be implemented as soon as technological barriers are overcome because they lead to cost advantages next to environmental impact reductions. In addition there are also several environmental improvement options that are not or less clearly linked to a cost reduction. In these cases it will depend on the policy of companies or on government ruling, whether such “best available technologies” will be implemented or not.

Keywords: crystalline silicon, manufacturing and processing, environmental effect

1 INTRODUCTION

Within the CrystalClear project important progress has been made to quantify the life-cycle environmental impacts of crystalline silicon photovoltaic modules. An up-to-date set of Life Cycle Inventory data has been established and published for the technology status of 2004 [1], these data were subsequently updated to the status of end 2005 - early 2006 [2]. Based on these data Life Cycle Assessments have been made of present-day c-Si modules and PV systems [3, 4].

In this paper we investigate a number improvement options by which the environmental profile of c-Si PV systems can be improved with relatively simple measures.

We will start with an analysis of the existing environmental impacts and the major contribution to that impact. Subsequently we will review energy reduction options, options to reduce atmospheric emissions and to reduce the consumption of scarce resources. Then we investigate which possibilities exist to apply the design-for-recycling concept to silicon PV systems. Finally we summarize our main findings.

2 IMPACT ANALYSIS

First we will investigate where to focus our efforts on if we want to improve the environmental profile of crystalline silicon PV modules.

Based on LCI data collected for the years 2005/2006 [2], an analysis has been made of the impacts of c-Si module production. The results are shown in figure 1 where all impacts have been normalized to the total impacts of Western Europe as they were in 1995. The figure gives an indication which environmental impacts are most relevant for PV modules

It can be shown that in the impact categories for global warming and acidification at least 70% of the emissions are related to energy consumption, either directly as process energy in the PV value chain or indirectly as energy embedded in materials such as aluminium, glass. A significant part of the energy-related emissions are caused by electricity production in the conventional electricity supply system. Moreover, figure 1 shows that the contribution by lamination and framing materials is limited. Therefore process energy consumption is the most important target when we look for environmental improvement options.

Considering the input of primary energy, both via process energy consumption and material consumption, we can look at figure 2 for the contribution of the different production process steps. A break-down into process energy and material-embedded energy is given in figure 3, where we see that 58% is consumed as process energy and 42% as materials. The major part of the process energy use is in the production of poly-silicon from mg-silicon. Obviously there are two options to reduce this part:

1) reduction of process energy in the poly-Si production process, and
2) reduction of silicon consumption per Wp.

We discuss these options shortly below.

Reduction of energy embedded in other materials (i.c mg-Si, laminate, frame, other) can only be achieved realistically by reducing material consumption and/or recycling of those materials, and of course by selecting input materials with a low energy intensity, like secondary (=recycled aluminium). We will look further into that kind of improvement options as well.

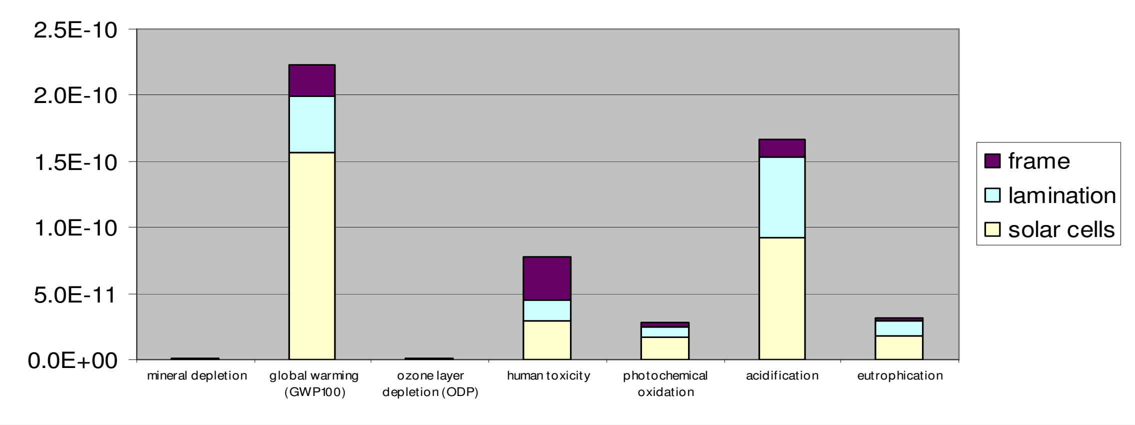

Figure 1: Normalized environmental impacts of 1 kWp of multi-crystalline silicon modules (CML 2000 method, normalisation W-Europe 1995, adapted depletion score[1])

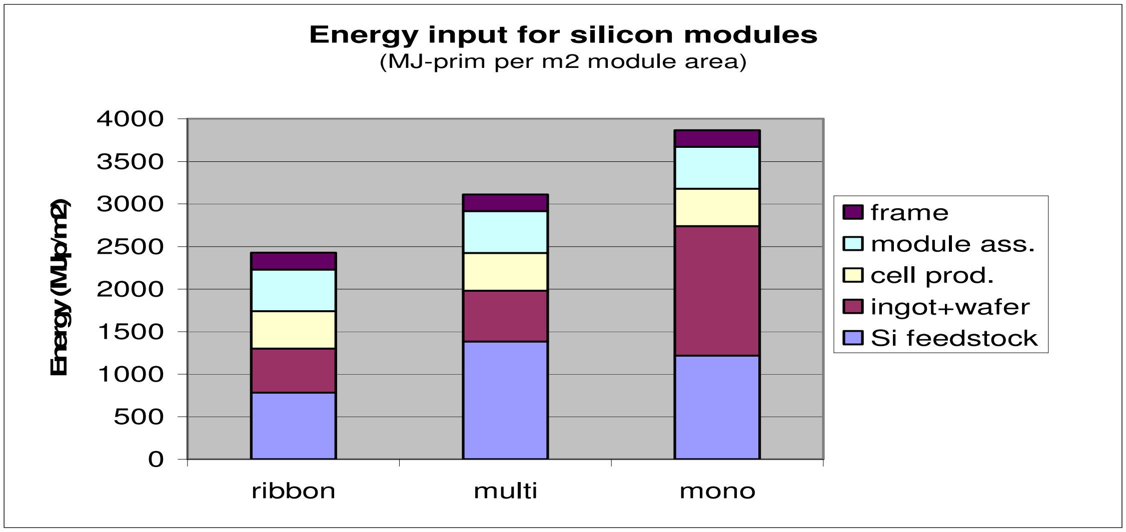

Figure 2: Input of primary energy for production of silicon modules (per m2 module area)

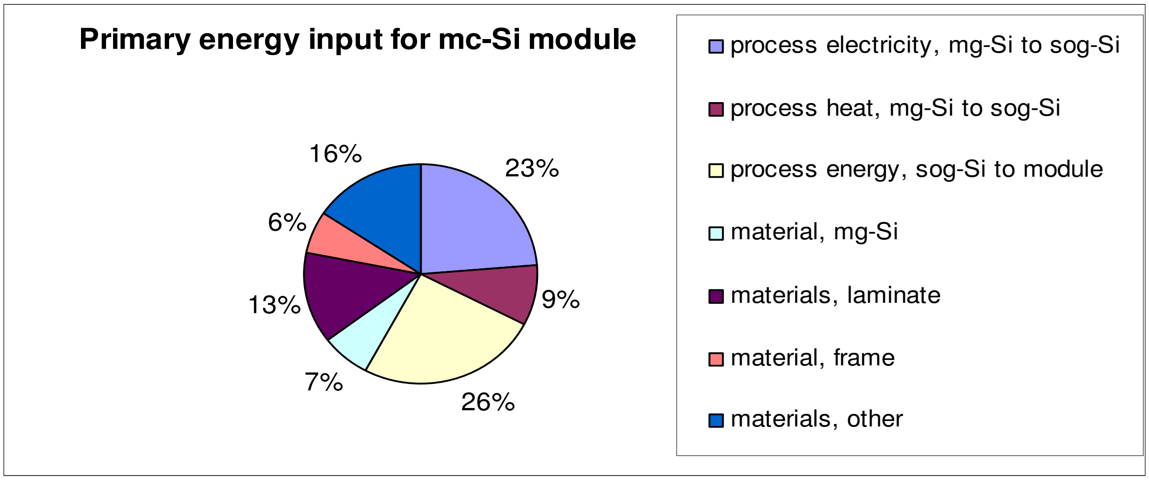

Figure 3: Break-down of primary energy inputs into process energy and materials

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[1] Impact score “abiotic depletion” of CML method was adapted to exclude fossil fuel depletion, new impact score was named “mineral depletion”.

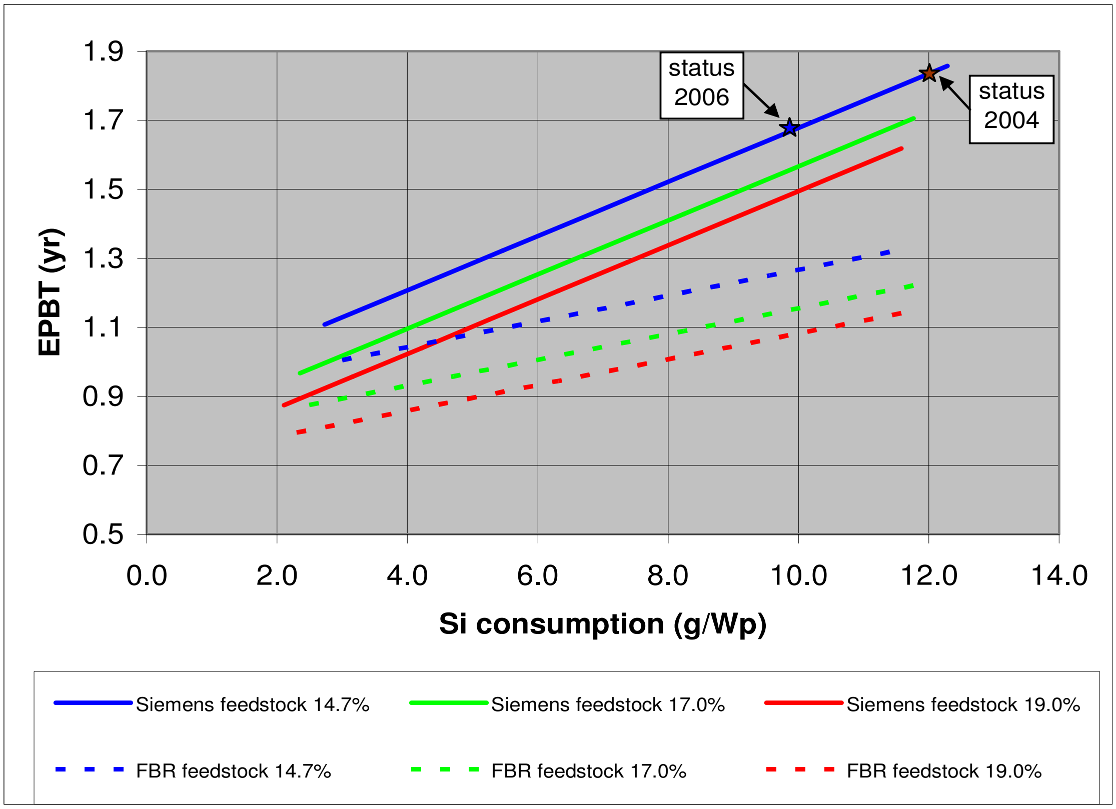

Figure 4: The Energy Pay-Back Time as a function of silicon consumption, for different combinations of a silicon feedstock process (Siemens, FBR) and multi-Si cell efficiency (resp. 14.7%, 17%, 19%). It is assumed that all other material and energy consumption for the module does not change, except that it is directly proportional to the module area. Module type: multi-Si module, frameless. System: roof-top system installed in S-Europe (1700 kWh/m2/y) with PR =0.75.

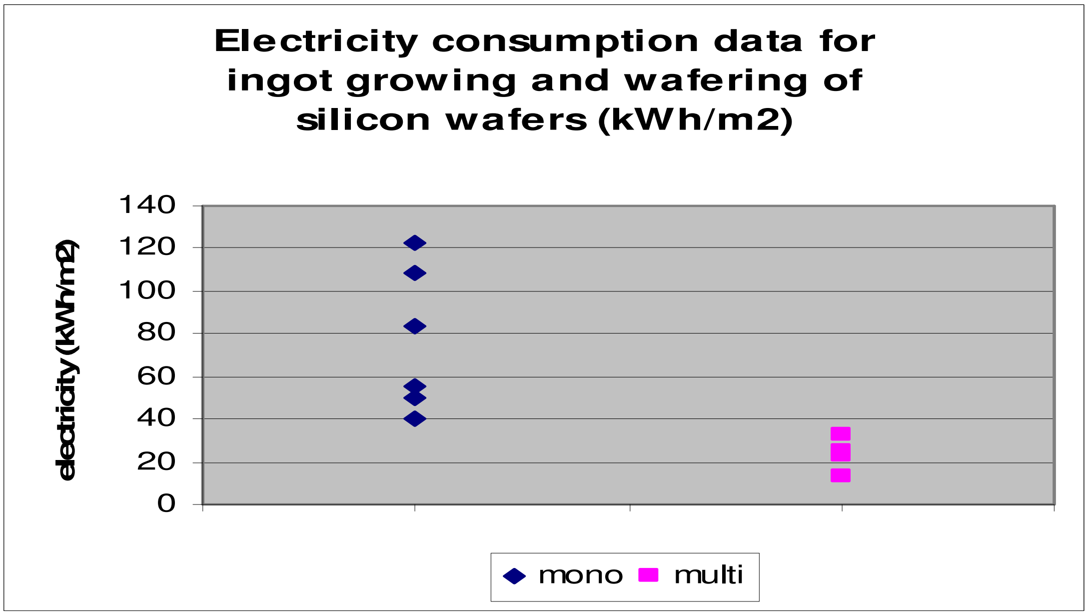

Figure 5: Variation in electricity consumption between different ingot/wafer manufacturers. Wafer thickness 240-270 um for mono-Si wafers, 200-240 um for multi-Si.

3 ENERGY SAVINGS OPTIONS

3.1 New silicon feedstock processes

We have seen that the process energy for production of poly-Si is responsible for more than 30% of the total primary energy input for a multi-Si module. On average about 110 kWh of electricity and 185 MJ of heat is used to produce 1 kg of poly-Si with the improved-Siemens process that is most common at this moment. Because of this high energy consumption energy costs are a significant cost driver, so that new processes, especially for solar grade silicon, are likely to have lower energy consumption.

The process that employs Fluidized Bed Reactors to replace Siemens reactors is reported to have much a lower *electricity consumption.* Reliable quotes for this technology are hard to come by, but it seems that a reduction to 30 kWh/kg Si is possible with FBR. Heat requirements, however, remain more or less the same. The Cumulative Energy Demand of sog-silicon, produced by an improved-Siemens process is estimated at 1070 MJ/kg, while for FBR-silicon we estimate it at about 500 MJ/kg.

For direct metallurgic processes that produce solar grade silicon directly from silica, also heat requirements may be reduced because the step of gas phase distillation is omitted. A published energy estimation for this process is 25 kWh/kg (≈300 MJ/kg) [5].

Figure 4 gives an indication of the effects that adoption of the FBR process instead of the Siemens process would have on the Energy Pay-Back Time of a PV system based on multicrystalline silicon modules. From the figure it is clear that new feedstock processes can give a dramatic improvement in the environmental profile of PV systems. On top of this other improvements are feasible, as is discussed below.

Barriers for the introduction of new feedstock process are the technological complexity, incomplete understanding of the allowable impurity levels and the high capital requirements for commercial scale plants. However, due to the present silicon scarcity several plants based on new process technology are now under construction.

3.2 Reduction of silicon consumption

The effect of reduced silicon consumption (in g per Wp) has been depicted in Figure 4. Observe that silicon consumption has decreased significantly over the past 2 years, driven by the silicon shortage.

Obvious ways to reduce silicon consumption are:

- improved crystallization with lower loss
- thinner wafers
- lower kerf loss
- reduce wafer breakage
- recycling of silicon waste from
  - ingot cut-offs
  - broken wafers
  - kerf loss
- casting or pulling wafers directly from liquid Si (ribbon technologies)
- increased cell efficiency

Almost all of these approaches are already followed within the PV industry and most are also part of the CrystalClear activities. A silicon consumption of 4-6 g/Wp seems to be well in reach within a few years. [6, 7]

The recycling of silicon kerf loss is – to our knowledge – not done anywhere on a commercial scale, but research on it has been conducted within the FP5 project RE-Si-CLE. If such a process becomes available and does not require to much energy it could substantially reduce silicon consumption by perhaps 30-40%.

Ribbon technologies for producing wafer directly from liquid silicon are in commercial operation and require 7-8 g silicon per dm^2, but cell efficiencies are still lower than for conventional wafers at 12.5-14%, so Si consumption per Wp is 5-6 g. For this reason ribbon-Si modules currently have the lowest energy pay-back time (1.5 yr) among all silicon technologies[2].

Barriers for (further) reduction of silicon consumption are manifold: silicon quality issues (Si recycling), sawing, cell and wafer handling (thinner wafers), cutting wire strength (kerf loss).

3.3 Increased energy-efficiency in ingot growing

From figure 2 we have seen that ingot and wafering represent a considerable part of the energy input for a module, especially for mono-Si material. At the same time we can observe that considerable differences in electricity consumption exist which mainly arise in the process of ingot growing (figure 5). From the background data we also observe a tendency that newer installations have lower electricity consumption. This would imply that there is considerable scope for improvement of the energy efficiency in ingot growing.

One aspect of increased efficiency in newer facilities is probably the larger batch size, which naturally reduces energy losses from the containers of molten silicon.

When looking at the process sequence of the crystal growing process, with its cycle of melting silicon and then slowly cooling it down again, it seems sensible to investigate the possibility of heat recuperation. For example one could think of using the waste heat from the ingot that is cooled down to preheat the next batch of silicon.

Barriers for improved energy efficiency in ingot growing are probably: a lack of urgency (cost advantages unclear), a focus on material quality and long lifetimes of crystal growing equipment.

3.4 Slurry recycling

The slurry consisting of SiC and polyethylene glycol (PEG) which is used in wafer sawing represents a fairly high energy value of about 30 MJ per m^2 wafer (about 20% of the total wafer energy requirement). SiC is the most energy-intensive component of the slurry with about 10 MJ/kg.

Until a few years ago slurry recycling was not a standard practice in wafer cutting plants, but over the last few years this practice has gained wider acceptance. Slurry recycling can be performed in-house at the wafering facility but often it is done by specialized companies like SiC Processing. In the slurry recycling process on average about 90% of SiC and 85% of the

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[2] Note that EPBT values for ribbon technology cannot be derived from Figure 4 because this figure assumes conventional ingot and wafering processes. See [4] for EPBT values of ribbon and other cell technologies.

PEG is recovered at fairly low energy costs of about 1 kWh/l slurry.

All-in-all the slurry recycling can reduce the wafer energy requirement with some 15%, while it also has cost advantages.

3.5 Increased energy-efficiency in cell processing and module assembly.

In cell processing variations between factories in energy consumption per unit product can also be observed but they are less pronounced then for ingot growing. The energy use of overhead facilities such as climate control equipment, DI water production and compressed air supply can be a significant part of the total plant consumption and therefore needs attention.

One trend which could negatively affect the energy efficiency is the increased use of clean room facilities in cell processing. If implementation of clean room processing is considered it would be wise to restrict the parts of the process line which operate under clean room conditions and to pay attention to an energy-efficient design of the air handling system.

In module assembly the process energy consumption is relatively low. The lamination step is of course the most energy consuming. The use of fast-cure EVA formulations will probably reduce the energy consumption of the laminator.

A significant energy input is required for aluminium frames around the module. A typical frame can contribute 8% to the total energy requirement of a module. Frameless modules, if they have the same, long life time as framed modules, are therefore preferable from an energy point-of-view.

3.6 End-of-life recycling of module materials

Apart from energy reduction options in the production stage we should of course also look at the waste phase of the photovoltaic module. Reuse or recycling of module materials will help to reduce the energy consumption in the module life-cycle.

Obvious examples are the recycling of aluminium frames and glass sheets. The energy requirement for secondary aluminium can be as low 8 MJ/kg, while primary aluminium requires 200 MJ/kg.

Also the recovery and reuse of silicon wafers from waste modules can reduce the energy consumption significantly, namely by roughly 25% on a module level.[8, 9]. A bottleneck for module recycling and wafer reuse is that it is rather difficult to extract wafers from a laminate without breaking them. With future thinner wafers this will become even more difficult.

4 REDUCTION OF AIR EMISSIONS

In chapter 2 we have seen that most emissions in module production are related to the energy consumption, i.e. they are produced during electricity or heat generation. There are a few process steps where air emissions may occur directly from the process itself:

- in silica reduction a CO_2-emission of 5 kg per kg Si occurs but part of this is CO_2 from biogenic origin. This emission cannot be easily avoided, but of course extended use of biogenic materials would reduce the net global warming effect of this emission.
- In cell processing fluorinated gases are used by some manufacturers, mostly for edge isolation and reactor cleaning after deposition of silicon nitride or film silicon. If no abatement equipment is installed –as is still the case in some facilities - FC emissions may occur. These gases are greenhouse gases with a fairly high GWP value. Some companies still use CF_4 in edge isolation although it is not state of the art anymore because of high wafer breakage rates. Based on a recent survey we estimate that the companies without abatement emit roughly 0.8 g CF_4/m^2 [10], which is equivalent to a greenhouse gas emission of 40 g CO_2-eq/Wp. For this estimate we assumed a CF_4 utilization in the production process of 10%. Accounted over the life time of a PV system in South-Europe this emission value would correspond to a GHG emission of 1 g $CO_{2\text{-eq}}$ per kWh generated for the modules produced by these companies.

  Although this is not a very large fraction of the total GHG emission for module production (≈ 1000-1200 g $CO_{2\text{-eq}}$/Wp), it also easily avoidable. More information on fluorinated gases emissions and abatement can be found in [10].

- When multicrystalline wafers are etched with nitric acid the etching reaction will also release a certain amount of NO_x-gas. If no gas washing is in place this will result in significant NO_x-emissions. With scrubbers in place NO_x-emission can be reduced by 30-90%[10]. For example in the production of wafers for the semiconductor industry relatively high NOx-emissions are reported [11]. Although it is known that for solar wafers much less etching is done, this NOx-emission is still a point of attention.

- Small quantities of lead may be released during the firing of the pastes and/or the soldering of cells. Removal of lead from the solder and pastes will avoid this emission.

- Small amounts of Volatile Organic Compounds (VOC's) from wafer cleaning and paste firing may be released. Proper equipment will help to abate these emissions.

The main bottleneck for adopting the measures above is probably that module manufacturing is not perceived as major source of harmful emissions, nor by companies themselves nor by authorities. And while this is true in absolute terms, we think that the PV industry should also regard as it as their mission to deliver a product which as environmentally compatible as possible, by adopting the "Best Available Technologies" for pollution control. Measures to decrease emissions add cost but have no increase in product quantity and quality.

5 REDUCTION OF THE CONSUMPTION OF SCARCE RESOURCES

5.1 Silver consumption

In the LCA results in section 2 we have observed that the use of silver in metal contacts contributes to the impact score for resource depletion. Although the contribution from silver to this score is relatively small

(≈1.5%), silver consumption could become a limiting if solar cell production is scaled up to GWp-levels [12].

Silver is a scarce resource already at the current global consumption rate. Economic reserves may be depleted after 20 years and the reserve would suffice for about 27 years [13]. Rapid PV deployment would cause silver resources to be depleted several years earlier.

Contacting solutions which do not need silver, would help to avoid such problems.

5.2 Water consumption

The consumption of water in PV module manufacturing is relatively high, although not as high as in the semiconductor industry. Water is mainly used for wafer and glass rinsing. We estimate the consumption for the whole PV module value chain at about 10 m^3/kWp. Whether water consumption is actually a problem or not depends very much on the production location.

After use the water can be treated and released to surface waters without any problem. Intelligent measures to reduce water consumption or to reuse process water can be helpful in places where water resources are scarce.

6 DESIGN-FOR-RECYCLING

The concept of design-for-recycling aims to design products in such a way that - at the end of its useful life - it is relatively easy to disassemble the product into separate components that can be reused or recycled. With respect to PV systems we can discern the following parts where design-for-recycling could be useful:

- aluminium frames from modules
- glass from modules
- silicon wafers from modules
- aluminium and steel parts from mounting structures
- casings for inverters

N.B. Recycling of copper from cables is already a standard practice. Recycling of plastic components, on the other hand, is usually not practicable.

With respect to PV modules the design-for recycling concept appears to be in conflict with the requirement that the module must be able to withstand 20-40 years of outdoor conditions. Standard EVA lamination makes the present-day module a very reliable product but also very difficult to disassemble. The only practical way to disassemble such modules seems to be by means of a high temperature process in which the EVA is burned away [9].

It seems doubtful, whether alternative lamination materials could be developed which combine the requirement of long outdoor lifetimes and easy dismantling at the end of life.

Entirely different module concepts in which no lamination is necessary, like the NICE technology, would greatly facilitate recycling of the silicon wafers [14]. Chemical treatments to etch away contact layers from solar cells have been developed successfully over the last years, for example at Deutsche Solar [8, 9].

The main bottleneck to the investigation and adoption of new module concepts is the – understandable – conservatism of PV module manufacturers. Over the past decades they have developed a module lamination process which delivers a robust product that has guaranteed lifetimes

For the BOS components mentioned above special efforts to develop new concepts for easier recycling, seem less important. With proper attention in the system dismantling stage separation of recyclable materials should be relatively easy.

7 OUTLOOK

If we combine a number of improvement options which are already available or will become feasible within the next 3-5 years, we can analyse the total overall improvement that is possible. For this we focus on multicrystalline silicon technology and we assume the use of Fluidized Bed Reactor technology for silicon feedstock material, best available technology for ingot casting, 150 um wafer thickness, 17% module efficiency and no F-gas emissions. As an extra case we assume that PV operations, from ingot casting to module, will be run on “green” electricity supply, namely wind power. (The FBR feedstock process was in both cases assumed to run on hydropower.)

Figure 6 shows the resulting Energy Pay Back Time (EPBT) and the life-cycle greenhouse gas (GHG) emission for a roof-top PV system in South Europe (irradiation 1700 kWh/m2/yr, PR=0.75, PV system lifetime = 30 year). No improvements in BOS or in PR have been assumed.

We can see that the EPBT can be reduced by 50%, to well below 1 year, while the case of wind electricity obviously makes no further difference for the EPBT. With respect to greenhouse gas emissions the present emission of 30 g/kWh can be reduced to about 15 g/kWh, and with the additional switch to green electricity supply even to 10 g/kWh. At this latter value the GHG emission of c-Si PV technology gets in the same range as wind energy and other low-carbon energy options [4].

8 SUMMARY AND CONCLUSION

In this paper we have reviewed a number of options to achieve a further reduction of greenhouse gas emissions in crystalline silicon module production. In the table below we have summarized the discussed options together with indications of the potential impact reductions, the question whether there is a synergy with cost reduction, and the barriers that the authors see for the adoption of these measures.

We can conclude that are a few options with a high to very high impact reduction potential which *also* have significant cost advantages. This means of course that these options have a high chance of being realised once the technology is available.

Other options, however, have little or even negative cost effects. In these cases it will depend on the policy of companies, whether they choose for implementing best available technologies for emission reduction or not. Increased transparency on energy and material consumption, environmental emissions and waste production will help to increase public awareness and thus influence company policies on this point.

Measure	**Reduction potential**	**Synergy with cost reduction**	**Main barriers for adoption**
New silicon feedstock process with reduced energy consumption	+++	yes	Technological complexity, material quality, capital requirements
Reduction of silicon consumption	++	yes	Wafer quality, sawing techn., wafer handling, wire strength
Improved energy-efficiency in ingot growing (mono+ multi)	+	somewhat	Uncertainty about cost, lack of urgency, long equipment life
Slurry recycling	+	yes	Concerns about quality loss?
Improved energy-efficiency in cell and module manufacturing	+	little	No sense of urgency
Frameless modules	+	Probably not	Concern for module lifetime
EOL recycling of modules	+	Uncertain	Module disassembly is quite difficult; long module life times make it difficult to organise take-back system
Abatement of FC gas emission	+	none	No sense of urgency, higher costs
Abatement of NOx emission from etching process	?	none	No sense of urgency, higher costs
Lead-free pastes and solders	+	none	Technical problems, low sense of urgency
Reduced water consumption	Location dependent	None	No sense of urgency, higher costs
Contacting without silver	+	perhaps	No good candidate available yet
Design-for recycling module concept	++	?	No good candidate available yet, low sense of urgency

Table 1: Overview of environmental improvement options, their synergy with cost reduction, and the main barriers for adoption.

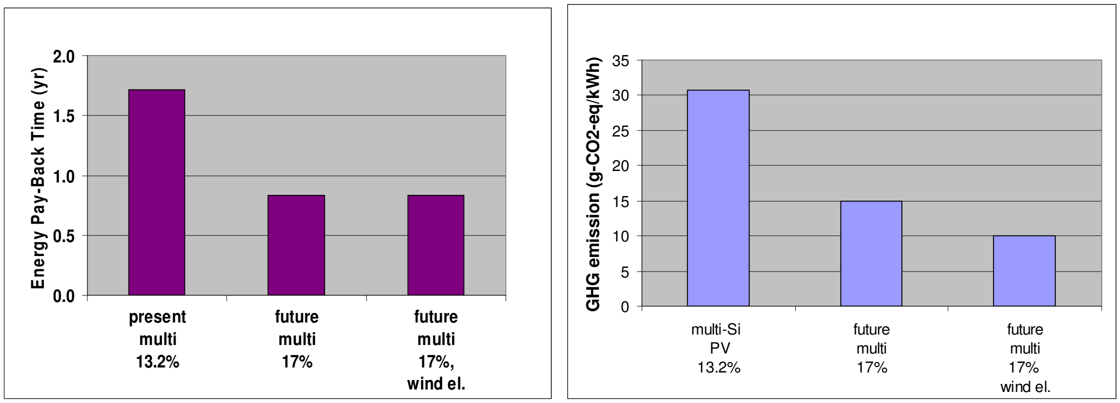

Figure 6: Potential improvements in energy pay-back time (in years, left) and greenhouse gas emissions (in g/kWh, right) for a multicrystalline silicon roof-top PV system in South Europe (irradiation 1700 kWh/m2/yr).

Altogether we have shown that there are good possibilities to reduce the Energy Pay-Back Time of a multicrystalline silicon PV system from today's 1.7 years to less than 1 year (roof-top system in South Europe). Life-cycle greenhouse gas emissions for such a system can be reduced from 30 g/kWh to 15 g/kWh or less.

ACKNOWLEDGEMENT

This study was conducted within the framework of the Integrated Project CrystalClear, a research and development project on advanced industrial crystalline silicon PV technology. This project is supported by European Commission under contract number SES6-CT_2003-502583.
For more information on the CrystalClear project: http://www.ipcrystalclear.info/

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