Measures to reduce environmental impacts could also lead to a cost reduction in the manufacture of crystalline silicon modules. But what are the most important options to reduce environmental impacts and what are the main barriers to their implementation? Erik A. Alsema and M.J. de Wild-Scholten deliver some answers.

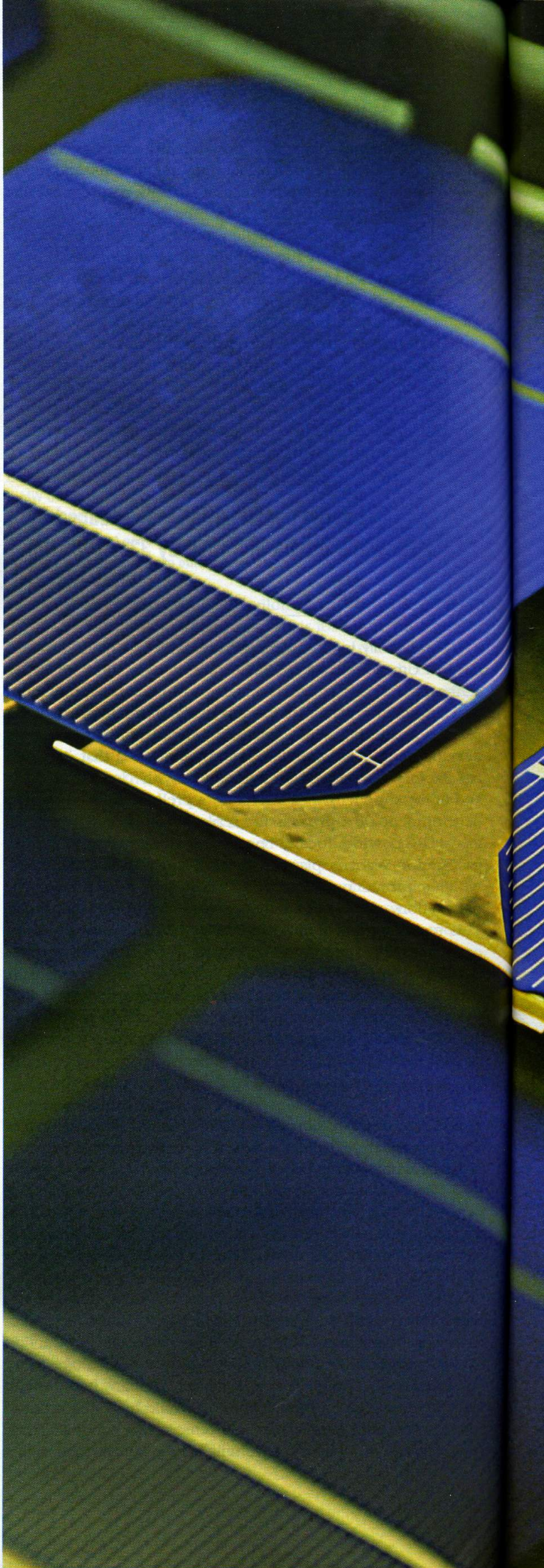
A reduction of silicon consumption in the PV manufacturing process is an obvious measure which may significantly reduce environmental impacts. In addition, silicon feedstock processes with lower energy consumption, such as fluidized bed reactor (FBR) technology, also have a large impact-reduction potential and both measures also have a cost saving potential.

Collectively such measures can reduce the energy pay-back time of a PV installation in southern Europe to well below one year.

Furthermore, improvements in crystal growing and cell and module manufacturing – as well as a number of options that are likely to be implemented as soon as technological barriers are overcome – are expected to lead to further cost advantages and environmental impact reductions. In addition, there are also several environmental improvement options that are less clearly linked to a cost reduction and in these cases progress on whether such 'best available technologies' will be implemented or not will depend on the policy of companies or on government rulings.

LIGHT IMPACT

An analysis of existing environmental impacts of present-day crystalline silicon (c-Si) modules and PV systems reveals a number of improvement options by which the environmental profile can be positively modified with relatively simple



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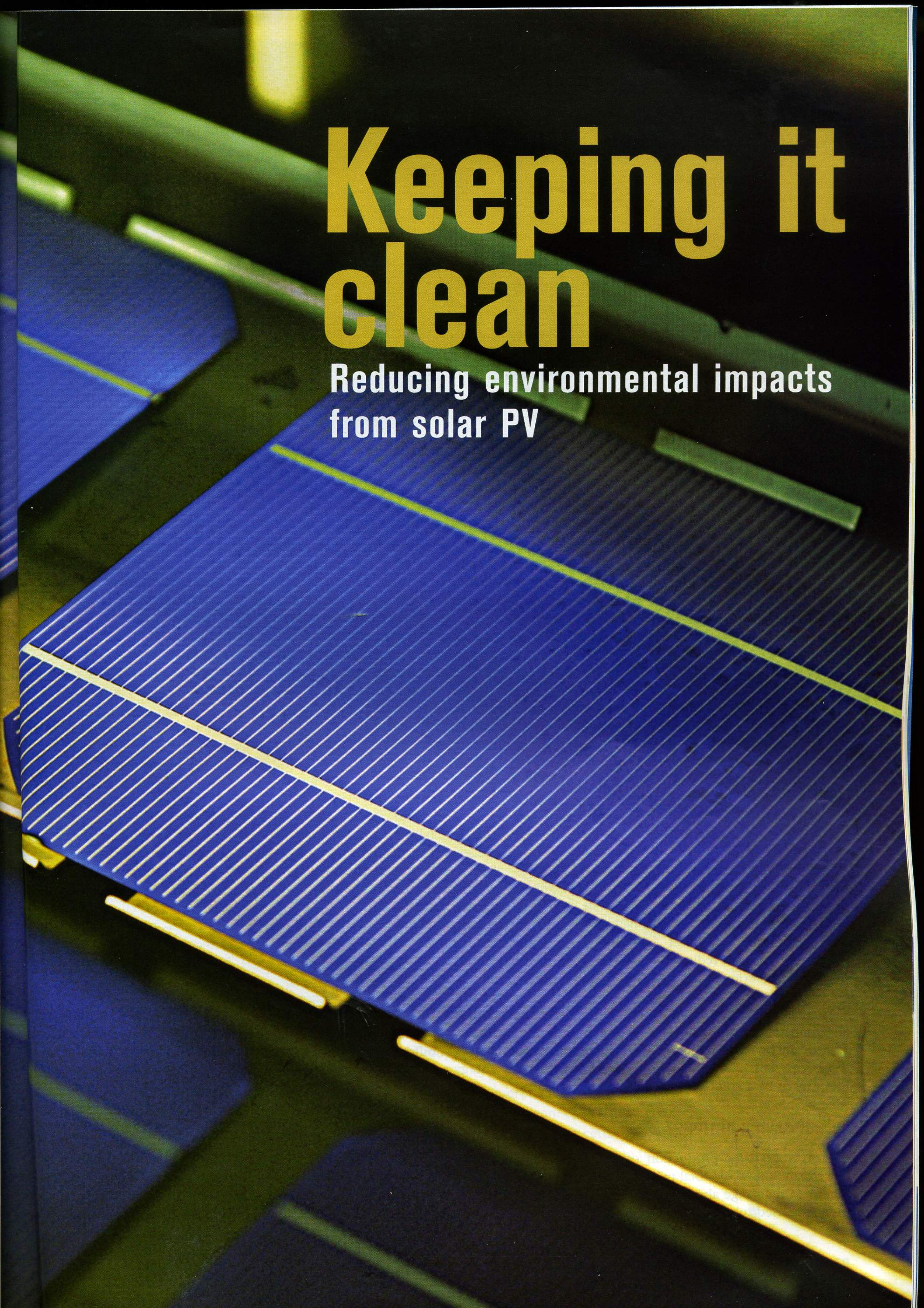
Keeping it clean

Reducing environmental impacts from solar PV



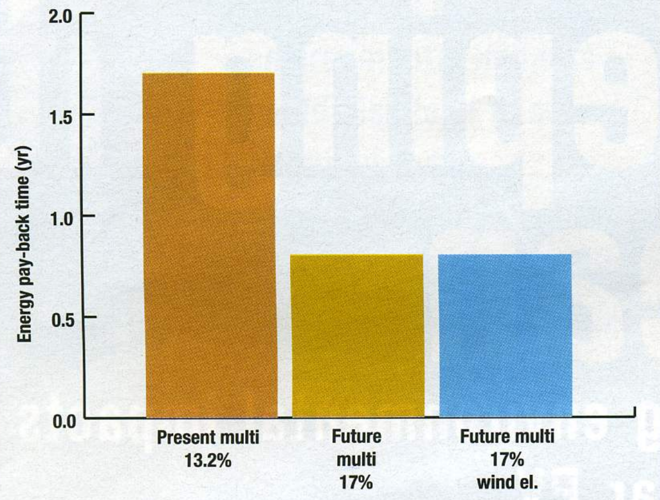


FIGURE 1. Energy pay-back time for future silicon PV

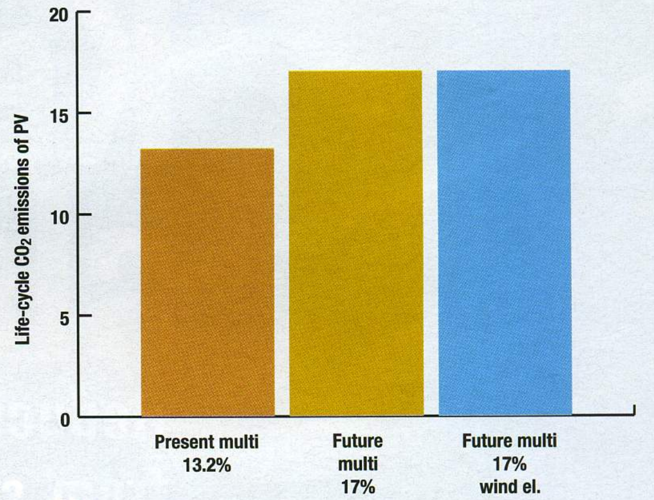


FIGURE 2. Life-cycle CO_2 emissions of PV

measures. Options to reduce energy consumption, atmospheric emissions and the consumption of scarce resources are all valid and possible, as is the application of the design-for-recycling concept to silicon PV systems.

Within the European Commission supported CrystalClear programme, a research and development project on advanced industrial crystalline silicon PV technology, important progress has been made to quantify the life cycle environmental impacts of crystalline silicon photovoltaic modules. Based on data collected for 2005–6, analysis shows 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 and glass. The contribution by lamination and framing materials is limited while a significant proportion of the energy-related emissions are caused by electricity production in the conventional electricity supply system. Process energy consumption is therefore the most important target for environmental improvement options.

Considering the input of primary energy, both via process energy consumption and material consumption, a breakdown reveals that 58% is consumed as process energy and 42% as energy embedded in materials. The major part of the process energy use is in the production of poly-silicon (poly-Si) from metallurgical-grade silicon and there are two obvious reduction options: a reduction of process energy in the actual poly-Si production process, and a reduction of silicon consumption per Wp.

Reducing energy embedded in other materials such as mg-Si, laminate, frame and such like can only be achieved realistically by reducing material consumption, by recycling of those materials, by selecting input materials with a low energy intensity or by a combination of the three measures.

ENERGY-SAVING OPTIONS

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 commonly in use. This high energy consumption makes energy costs a significant driver, so that new processes, especially for solar grade silicon, are likely to have lower energy consumption.

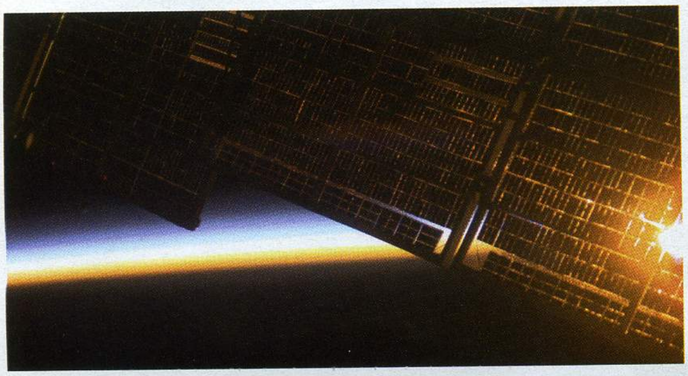
A process that employs fluidized bed reactors to replace Siemens reactors is reported to have much lower electricity consumption, and while reliable data for this technology are hard to come by, it seems that a reduction to 30 kWh/kg Si is possible. Although heat requirements remain more or less the same for both processes, the cumulative energy demand for silicon produced by an improved-Siemens process is estimated at 1070 MJ/kg, while that for FBR-silicon is estimated at about 500 MJ/kg.

For direct metallurgic processes that produce solar grade silicon directly from silica, heat requirements may also be reduced because the gas phase distillation stage of the process is omitted. An energy estimate for this process is 25 kWh/kg or some 300 MJ/kg.

Adoption of the FBR process instead of the Siemens process would clearly have a dramatic effect on the energy pay-back time of a PV system based on multicrystalline silicon modules. And, while barriers for the introduction of new feedstock process remain – such as the technological complexity, incomplete understanding of the allowable impurity levels and the high capital requirements for commercial-scale plants – due to the present silicon scarcity several plants based on new process technology are now under construction.

Ingot and wafering production 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. 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



Solar photovoltaic technology can become even more environmentally friendly NASA

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.

Variations in energy consumption per unit product between factories is less pronounced than for ingot growing, but the energy use of overhead facilities such as climate control equipment, de-ionized water production and compressed air supply can be a significant part of total consumption.

One trend that 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 necessary 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 intensive, but 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 life span as framed modules, are therefore preferable from an energy point of view.

REDUCTION OF SILICON CONSUMPTION

Silicon consumption, in g/Wp, has already decreased significantly over the past two years, driven by the silicon shortage. Obvious ways to reduce silicon consumption are improved crystallization with lower loss, thinner wafers, lower kerf loss and reduced wafer breakage, recycling of ingot cut-offs, ribbon technologies and such like. Almost all of these approaches are already used within the PV industry and it seems that a silicon consumption of 4–6 g/Wp could be in reach within a few years.

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

Ribbon technologies for producing wafers directly from liquid silicon are in commercial operation and require only 7–8 g silicon/dm^2. Cell efficiencies are still lower than for conventional wafers at 12.5%–14%, so Si consumption per Wp is 5–6 g. Even so, at 1.5 years, ribbon-Si modules currently have the lowest energy pay-back time among all silicon technologies.

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/m^2 wafer or about 20% of the total wafer energy requirement. SiC is the most energy-intensive component of the slurry with about 10 MJ/kg. Until recently slurry recycling was not a standard practice in wafer cutting plants, but over the last few years this practice has gained wider appeal.

Slurry recycling can be performed in-house at the wafering facility but is often done by specialized companies like SiC Processing. In the slurry recycling process on average about 90% of SiC and 85% of the PEG is recovered at fairly low energy costs of about 1 kWh/litre slurry. All-in-all the slurry recycling can reduce the wafer energy requirement by some 15%, and also has other cost advantages.

Although prospects for further reduction of silicon consumption look promising, there are still a number of technological problems that have to be resolved: silicon quality issues related to silicon recycling, sawing, cell and wafer handling of ever thinner wafers, cutting wire strength and kerf loss.

EMISSIONS REDUCTION

Most emissions associated with module production are related to energy consumption, but there are a few process steps where air emissions may occur directly from the process itself. For instance, ?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 extended use of biogenic materials would reduce the net global warming effect of this emission.

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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 greenhouse gases emissions may occur. Some companies still use CF4 in edge isolation, although it is not state-of-the-art any more because of high wafer breakage rates. Based on a recent survey, companies without abatement are estimated to emit roughly 0.8 g CF4/m^2, equivalent to 40 g CO_2-eq/Wp. Accounted over the lifetime of a PV system in south Europe such an emission value would correspond to a GHG emission of 1 g CO_2-eq per kWh generated. Although this is not a very large fraction of the total at 1000–1200 g CO_2-eq/Wp of GHG emissions for module production, it also easily avoidable.

Other examples of processes causing emissions include nitric acid etching of multicrystalline wafers, which releases a certain amount of NOx-gas. If no gas washing is in place this will result in significant NOx-emissions, but with scrubbers in place NOx-emission can be reduced by 30%–90%.

Small amounts of volatile organic compounds (VOCs) from wafer cleaning and paste firing may also be released. Proper equipment will help to abate these emissions while a switch to lead-free solder and pastes can eliminate the small quantities of lead that may also be released during the firing of the pastes and/or the soldering of cells.

One obstacle to adopting measures to minimize emissions is probably that module manufacturing is not perceived as a major source of harmful emissions either by companies themselves or the authorities.

Another issue to consider is the consumption of relatively less abundant materials. The use of silver in metal contacts contributes to resource depletion and although the contribution from silver is relatively small, it could become a limiting factor if solar cell production is scaled up to GWp-levels.

Silver is already a scarce resource at the current global consumption rate, with economic reserves possibly depleted after 20 years and reserve sufficient for about 27 years. With current technology, rapid PV deployment would cause silver resources to be depleted several years earlier, though contacting solutions which do not need silver would help to avoid such problems.

The consumption of water in PV module manufacturing is also relatively high, although not as high as in the semiconductor industry. Water is mainly used for wafer and glass rinsing. Consumption for the whole PV module value chain is estimated 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 problems, but intelligent measures to reduce water consumption or to reuse process water can be helpful in places where water resources are scarce.

DESIGN FOR LIFE

As well as energy and materials reduction options in the production stage, the waste phase of the photovoltaic module must also be considered. 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 by roughly 25% on a module level. One bottleneck to greater module recycling and wafer reuse is difficulty of extracting wafers from a laminate without breaking them. With wafers anticipated to become thinner over time this issue will become even more difficult to overcome. Chemical treatments to etch away contact layers from solar cells so that the wafers may be reused to manufacture new cells have been developed successfully in recent years, for example at Deutsche Solar.

The concept of design-for-recycling aims to design products which are relatively easy to disassemble into separate components that can be reused or recycled. With respect to PV systems, design-for-recycling could be useful for components such as aluminium frames, glass and silicon wafers from modules, aluminium and steel parts from mounting structures and casings for inverters. 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.

It seems doubtful whether alternative lamination materials could be developed that combine the dual requirements of a long outdoor lifetime and easy dismantling. Entirely different module concepts in which no lamination is necessary, like NICE technology, would greatly facilitate recycling of the silicon wafers. Nonetheless, the understandable conservatism of PV module manufacturers remains a major stumbling block to the investigation and adoption of new module concepts.

HOW CLEAN IS YOUR HOUSE?

The number of improvement options either currently available or that will become feasible within the next three to five years can yield impressive improvements in both environmental and commercial performance. Focusing on multicrystalline silicon technology and assuming the use of fluidized bed reactor technology for silicon feedstock material, best available technology for ingot casting, 150 μm wafer thickness, 17% module efficiency and no F-gas (fluorinated greenhouse gas) emissions, the resulting energy pay-back time for a roof-top PV system in southern Europe can be reduced by 50% and well below one year.

With respect to greenhouse gas emissions, current emissions of 30 g/kWh can be reduced to about 15 g/kWh, and with an additional switch to green electricity supply for the manufacturing process, can shift this figure to as low as 10 g/kWh. At these values, the GHG emission of c-Si PV technology is in the same range as wind energy and other low-carbon energy options.

Certainly, there 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 realized once the technology is available. Other options, however, have little or even negative cost effects. In these cases it will depend on the policies of individual companies and whether they choose to implement best available technologies for emissions reduction or not.

But, increased transparency on energy and material consumption, environmental emissions and waste production will help to increase public awareness of the issue and thus influence company policies on this point.

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