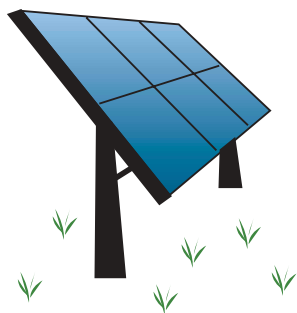


TOWARDS CLEANER SOLAR PV



Environmental and health impacts of crystalline silicon photovoltaics

Recent studies give the impression of photovoltaics having considerable environmental impact. Looking closer at the data however, it is clear that these studies are based on photovoltaic systems of the late eighties, with only minor recalculations. Since the photovoltaic market has increased rapidly, a lot of progress has been made regarding the environmental profile of photovoltaics. In this article Mariska de Wild-Scholten and Erik Alsema report on the improvements already achieved, those expected in the near future and the issues that need to be tackled for the development of crystalline silicon photovoltaics. They focus the discussion on multicrystalline silicon solar cells, the technology with the largest market share at present.

A recent report (World Energy Council, 2004) (*see Refocus weekly 2004-07-28, www.re-focus.net*) presents figures for the life-cycle carbon dioxide emission from PV systems with quite a large range from 12.5 to 104 tonnes of CO₂ equivalents for every GigaWatt-hour the PV system generates over its 30-year life. Taking a closer look at the highest value of 104 g CO₂ eq / kWh, we find that it was taken from the 2001 report "Coal in a Sustainable Society". The considered system is a solar farm in Australia. Because the energy production of a photovoltaic system in sunny Australia is among the highest in the world, one would not expect the highest CO₂ eq here. The fact that the energy used during the production of the PV systems is taken from the Australian grid, being supplied for 80% by brown and black coal electricity plants and 11% gas, explains the high value. Elsewhere, a 2003 report by the European Commission as a result of the ExternE project series (EC, 2003) presents external cost of photovoltaics of 0.6 euro-

cents / kWh, compared to 0.05 eurocents / kWh for wind energy, 3 eurocents / kWh for biomass, 0.2 eurocents / kWh for nuclear energy and 1-2 eurocents / kWh for gas. This study relies to a large extent on 25-year-old PV life cycle data, with only minor updates (de Wild-Scholten, 2004).

When looking at the life cycle inventory (LCI) data used in these two studies, it is clear that an update of PV life cycle data is necessary. To make an environmental comparison between different products, the method of environmental life cycle assessment (LCA) can be used, which takes into account material and energy input- and output from cradle to grave.

Approach

In 2003 we conducted an environmental life cycle assessment study on advanced production technologies for multicrystalline silicon PV systems (Alsema, 2003). A standard production route for multicrystalline silicon wafers was compared with two advanced routes, being: the production of solar grade

silicon via direct carbothermic reduction (Solsilc) route followed by the production of silicon sheets via the Ribbon-Growth-on-Substrate (RGS) route; and the production of solar grade silicon from purified silane (Joint Solar Silicon route) followed by the production of silicon sheets via the Edge-Defined-Film-Fed-Growth (EFG) route. The 2001 LCI data for the production of solar cells were taken from a West-European manufacturer. Several existing and advanced PV systems were considered. In this article we present key findings from this study and discuss in what ways photovoltaic technology may be improved further by ongoing R&D efforts.

Silicon feedstock

A very significant part of the environmental impact of PV systems is due to the energy consumed in the process for production of high-purity silicon feedstock. The silicon that is used in the microelectronics industry has to meet very high purity standards and therefore production techniques are used which require a lot of energy. Until a few

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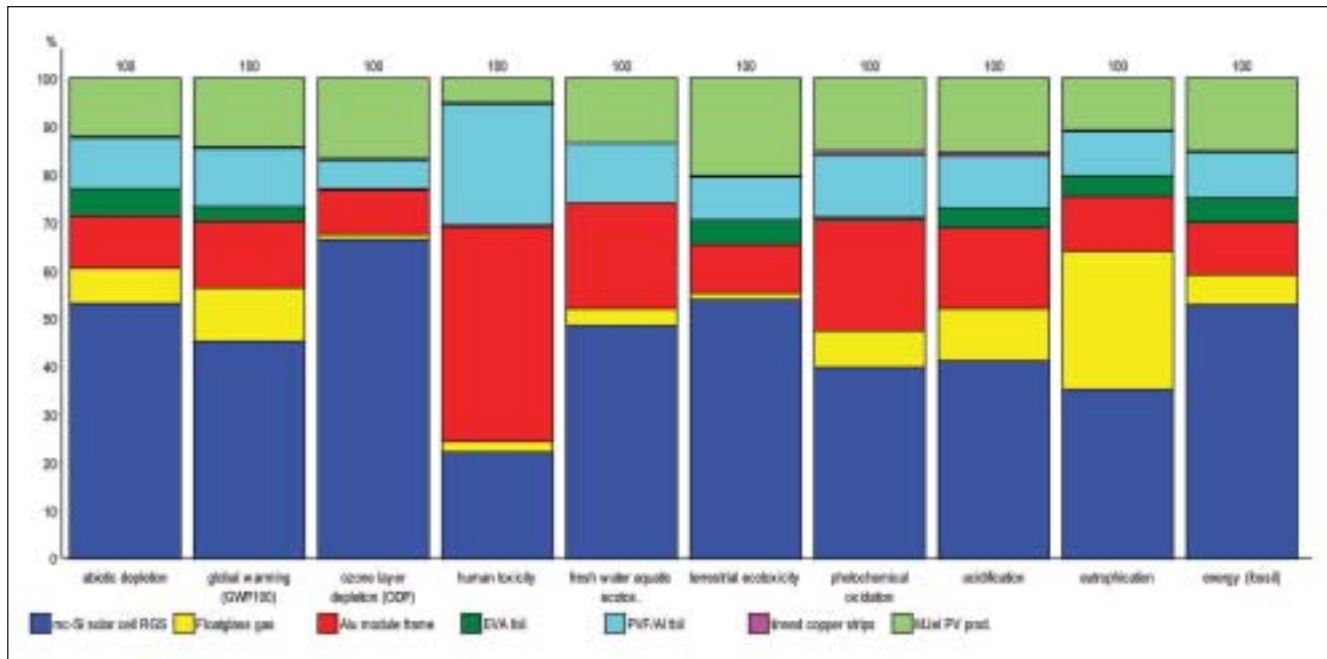


Figure 1: Breakdown of impact scores for one module containing RGS ribbons, with relative contributions from the solar cell, cover glass ("float glass"), aluminium frame, EVA, back foil ("PVF/Al"), connection strips ("tinned copper strips") and finally the electricity consumption for module assembly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

years back the photovoltaic industry mainly used scrap material from the electronic grade silicon production process. Because of the reduced demand from the microelectronics industry in recent years the excess silicon production capacity has been used to produce lower grade ("solar-grade") silicon with relaxed specifications in existing plants at reduced costs. However, with few exceptions (Wacker, SGS, which have dedicated former electronic grade silicon plants to production of solar grade silicon) this possibility will disappear soon as the silicon demand from the microelectronics industry picks up again. Also both production routes require a considerable energy input.

Many initiatives exist to develop new processes to produce dedicated solar-grade silicon, independent from the electronic-grade silicon production. It is hoped that these processes will provide a stable source of solar silicon at reasonably low costs and at lower energy inputs.

Silicon production via liquid phase

Elkem Solar in Norway has developed a process for the metallurgical refining of metallurgical grade silicon to solar grade silicon. Pilot production is planned for the near future. The energy consumption is estimated to be 25-30 kWh/kg product. This is a significant reduction, compared to the range of

values 120-160 kWh/kg found for the production of electronic grade silicon via the conventional Siemens bell-jar process. The production of solar grade silicon via the Solsilc route is similar to the production of metallurgical grade silicon from quartz and different carbon sources, but now with very clean starting materials. The energy consumption is similar to the Elkem Solar route. Interesting, from an environmental point of view, is the production of silicon without a carbon reductant via the electrochemical reduction of quartz, thereby reducing the emission of the greenhouse gas carbon dioxide. We are looking forward to the first solar cell efficiency results in this area.

Silicon production via gas phase

Joint Solar Silicon (a joint venture of Degussa and Solar World) is researching the decomposition of silane (SiH_4) in a tube reactor. A drawback of using silane may be the formation of unwanted fines and thereby reduction of the process yield. Wacker in Germany is developing a trichlorosilane fluidized bed process and thinks it will be possible to reduce the energy consumption on pilot scale to "about one third" of the value of the conventional process. This implies that it is below 50 kWh/kg. The decomposition of trichlorosilane produces hydrochloric acid, so exhaust gas treatment is necessary.

Other parties seriously investigating the production of solar grade silicon are Solar Grade Silicon LLC (SGS, a joint venture of REC and ASIMI), and Tokuyama's VLD (vapour to liquid drop).

By changing the form of the solar grade silicon products from rods (from the Siemens type reactor) or beads (from a fluidized bed reactor) to thin films, a high silicon reactant to product conversion efficiency may be achieved. Sugura Noda and colleagues from the University of Tokyo are developing this. Chlorosilanes are produced from metallurgical grade silicon and hydrochloric acid. The chemical vapour deposition process is designed with closed gas recycling, so the consumption of hydrochloric acid is small. The researchers are concentrating now on the production of monocrystalline thin films. No solar cells have been made yet. In conclusion, the solar grade silicon production techniques presently being prepared for pilot scale production, all seem to be able to produce at less than 50 kWh/kg. This would mean a large improvement over the present value, and a reduction of the energy pay-back time.

Ingots production

In order to prepare multicrystalline silicon ingots, the silicon is heated in quartz crucibles and cooled down slowly. The outer

edges of the ingot are cut off, because the material has insufficient quality. The sides, the bottom and part of the top are generally remelted to produce subsequent ingots. In our life cycle inventory we used a load of 150 kg silicon, but Deutsche Solar has demonstrated the growth of ingots up to 330 kg. The advantage of larger ingots is that a larger fraction of the ingot can be used for wafer and solar cell production.

Wafers

The crystalline ingots are subsequently cut into thin wafers. In our study the wire sawing of the ingots produces wafers of 300 micron thickness and an area of 12.5 x 12.5 cm². Improvements have been demonstrated in an industrial environment. Deutsche Solar has tested the multi-wire free-abrasive (not abrasive free!) slicing technology of HCT Shaping Systems and produced and processed 200 micron thick 12.5 x 12.5 cm² wafers. Although more wafers are lost during post-slicing handling, there is a saving on the silicon feedstock because of the thinner wafers.

Another concept which reduces silicon usage is the less than 70 microns thin Sliver® cell (1.7 g Si/Wp compared to 15 g Si/Wp in conventional PV panels). Because the cell processing is more complex, the energy needed to produce the bifacial modules is larger, but there is significant net benefit. The first modules should be commercially available from Origin Energy in

Australia in the first quarter of 2005. Elsewhere, the flexible Spherical Solar Power modules contain tiny crystalline silicon spheres (= cell), bonded between thin flexible aluminum foil substrates. The Canadian company wants to have the product available this year and plans to use only 9 g Si/Wp. During sawing a large amount of slurry is produced, which contains polyethylene glycol, silicon carbide, iron and silicon. Slurry recycling is gaining interest for environmental and economic reasons. The company "SiC processing" in Germany has SiC recycling plants in Bautzen, Germany and Navarra, Italy. The saw manufacturer HCT Shaping Systems is producing a slurry recovery unit. Sawing without slurry is possible with the diamond wire saw, but the high price of the wire is the major drawback. The Water Jet Guided Laser MicroJet® of Synova is a laser cutting system without slurry. Cutting waste is reduced to a minimum because ablated material is removed by the water, leaving the cut area clean. The cold cutting avoids structural damage, which results in higher efficiency solar cells.

Ribbons

Another approach is to avoid sawing entirely, by directly casting or pulling the molten silicon in the right shape. The defect structure present in the ribbon silicon wafers may limit material quality and cell efficiency. The direct casting Ribbon-Growth-on-Substrate (RGS) technology, being developed at the

Energy research Centre of the Netherlands, is now able to produce 4x5 cm² 12% efficiency cells with industrial-type processing. The direct pulling Edge-Defined-Film-Fed-Growth (EFG) technology, applied by RWE Schott Solar, is able to make 10x10 cm² 15% efficiency cells.

Cells

During the production of crystalline silicon solar cells chemicals are used. Several etching steps are necessary: removal of sawing damage, texturisation, to reduce the reflection (can be combined with saw damage removal) and phosphorus silicate glass (PSG) removal. Alkaline solutions like KOH or NaOH are used for texturing monocrystalline silicon solar cells. Industry is using this also for multicrystalline silicon, but less effectively, because of the different grain orientations. Research is focused now on wet acidic texturing with HF/HNO₃ solutions. In-line etching equipment is now available, which results in safer operation and less gas emissions, because there is no need anymore for cassette transfer of the wafers. These wet chemical etching processes result in waste solutions and high water consumption.

Dry etching has the drawback of using gases with high global warming potential, like perfluoro compounds (PFCs) and sulphur hexafluoride (SF₆). The global warming potential (GWP) of SF₆ for example is a factor 22200 larger than that of CO₂. Although these dry etching gases do not present a health hazard, the chemicals produced in the process may be toxic and/or polluting (SiF₄, HF) and need treatment. In the long term the substitution of these high-GWP gases by low-GWP gases is desirable. Dopant gases like POCl₃ and B₂H₃ and the gases SiH₄ and NH₃ used in the chemical vapour deposition process to make the Si₃N₄ anti-reflection coating, also pose a health risk.

All these chemicals do not end up in the module however. There is one toxic compound which does: lead. It is present in the tin-lead solders, used to interconnect the solar cells. RWE Schott Solar has developed an alternative, containing 96.5% tin and 3.5% silver, but this requires a higher working temperature. Also Mitsubishi is selling lead-free solder modules. The need for solders is not present in a new way of encapsulation in



Figure 2: PV module recycling furnace and module stack at Deutsche Solar. Source: Deutsche Solar.

which solar cells are connected by electrically conducting glues. The development is still in laboratory phase. Lead is also present in the screen printing pastes, used in the metallization. Several companies are involved in the development of lead-free pastes. Ferro has developed a lead-free / low-bow aluminium paste (CN53-100). No lead-free silver paste is on the market, but in the EC project EC2Contact promising results have been obtained to replace the lead in silver paste (results will be presented by Hoornstra at the 31st IEEE Photovoltaic Specialist Conference, Florida, 3-7 January 2005).

The WEEE (Waste of Electrical and Electronic Equipment) & ROHS (Restriction Of the use of certain Hazardous Substances) directives, which came into force 13 August 2004, are not applicable to solar panels. However in the future they may be included (see article 13 of the WEEE). This may have serious implication for the use of lead in modules (see *Refocus Weekly 2004-07-28*, www.re-focus.net).

Modules

A breakdown of the environmental impact scores for a module with RGS ribbons is presented in Figure 1. The encapsulation and framing of the modules uses energy-intensive materials such as glass and aluminium. The scores can be improved by using secondary (recycled) aluminium as much as possible or by making PV modules without a frame (called PV laminates). In our study we used a module efficiency of 12.1%, although some modules produced in 2004 using multicrystalline silicon solar cells have efficiencies above 14%.

Systems

The life cycle assessment of inverters is hampered by the fact that little data is available for electronic components. Often the first component of a grid-connected PV system which fails is the inverter, therefore the increase of its lifetime is necessary. Another point of attention is the possible presence of bromine containing flame-retardants, since these substances are included in the WEEE/ROHS legislation, which has the implication that the producer is responsible for the recycling of the inverter. Mounting frames to fix the PV modules on an existing roof use a lot of the energy-intensive material

aluminium. In the newly developed PV-Wirefree system some functions are combined, resulting in less material usage. It is based on parallel-connected PV modules using aluminium current carrying mounting frames. An advantage of parallel-connected PV modules is a significant increase of electricity output ranging from 2 to even 50% (not included in our LCA) due to a larger tolerance for partial shading.

Recycling of cells and modules

Deutsche Solar offers a general service for the recycling of PV modules with the major advantage that the silicon wafers can be reclaimed (Figure 2). It is important to supply the defect modules without additional unnecessary damage during dismounting and transportation, to ensure a high-value recycling. The thermal decomposition of the polymers used in the modules results in the release of fluorine containing compounds from the Tedlar and the release of acetic acid from the EVA (ethylene vinyl acetate), therefore the waste gas is treated in an afterburner and washer. The use of halogen-free polymers would make the waste gas treatment less complex. Tests have shown that solar cells prepared from reclaimed wafers may perform even better in their second life (due to improved solar cell processing techniques).

Energy payback time

In our study the calculated energy pay back time of a standard PV system is 4.8 years for grid connected systems in the Netherlands/Germany (at yearly electricity output of 750 kWh/kWp/yr) and 2.8 years for systems South-Europe (output 1275 kWh/kWp/yr). For an advanced PV-Wirefree system with modules containing RGS ribbons this is reduced to 2.0 years for the Netherlands/Germany and 1.2 years for South-Europe. In the past a large part of the energy consumption of PV manufacturing plants was overhead energy for facilities such as clean rooms and climate control. Shifting from batch to inline automatic processing may decrease this overhead energy in the future. As indicated in this article many improvements are under way, so we can expect a further reduction in the energy pay back time.

Outlook

There is a clear need for up-to-date LCA data, but unfortunately the PV industry is reluctant to share these data with LCA researchers. However, in the current EU integrated project Crystal Clear all main European crystalline silicon solar cell manufacturers have promised to provide new life cycle inventory data. Results will be available next year.

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Further information

For more information on this subject, we can recommend the portal about environmental, health and safety aspects of photovoltaics at: www.ecn.nl/zon/products/ehs/index.en.html.

On this page you can also find an overview of LCA projects of other PV technologies like the thin film amorphous silicon, CIGS and CdTe solar cells. You may subscribe to a mailing list, to receive news about this topic regularly.