

Environmental life-cycle assessment of multicrystalline silicon solar cell modules

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a study by commission of
the Netherlands Agency for Energy and the Environment,
NOVEM

September 1995

Report no. 95057

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Abstract

In this report the environmental aspects of solar cell modules based on multicrystalline silicon are investigated by means of the Environmental Life Cycle Assessment method. Three technology cases are distinguished, namely present-day module production technology, future probable technology and future optimistic technology.

For these three cases the production technology is described, the material requirements and environmental emissions are inventorised and the energy requirements and energy pay-back times are discussed.

Finally recommendations with respect to Dutch photovoltaic R&D policy are given.

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Note

This study was conducted by commission of the Netherlands Agency for Energy and the Environment, Novem. It is one in a series of studies on the environmental aspects of solar cell technologies. Earlier studies were focused at CdTe and CuInSe₂ [22], and amorphous silicon solar cell technology [5]. A summary report on the environmental aspects of the four considered cell technologies is in preparation.

Acknowledgements

First of all we want to thank Novem for their financial support and for their patience in waiting for the final report of this study. Furthermore we would like to thank the solar cell experts, who did not only provide us with invaluable information for our study, but who have also read critically the draft of this report: prof. dr. J. Nijs (Inter university Micro Electronics Centre, IMEC, Belgium), dr. W. Sinke (Netherlands Energy Research Centre, ECN) and Ronald van Zolingen (R&S Renewable Energy Systems b.v., Helmond, the Netherlands). Without their knowledge and comments on production technology, cell characteristics and future developments the current report would have lost much of its depth and accuracy.

Also we would like to thank dr. J. de Vos (Soltech, Belgium), dr. Holricher (Wacker-Chemitronic, Germany), dr. Koch (Bayer AG, Germany), dr. Hukin (Crystalox Ltd., England) and dr. H. Dawson of Advanced Silicon Materials Inc. (Moses Lake, WA, USA) for providing us with information which proved to be very useful.

1. Introduction

Photovoltaic (PV) energy conversion is increasingly regarded as a technology which may contribute to the mondial energy supply in a way that is compatible with the concept of sustainable development. However, to ensure that PV energy can indeed fulfil this expectation a careful consideration of potential environmental risks of PV energy conversion is necessary. In this way potential bottlenecks can be identified in time so that R&D priorities can be set accordingly to reduce or eliminate these bottlenecks. As a result of such an environmental assessment it might be decided for instance to start investigations on alternatives with regard to cell materials, production technologies or module encapsulation techniques.

Against this background Utrecht University was commissioned by the Netherlands Agency for Energy and the Environment (NOVEM) to conduct a study on potential environmental and safety risks for a number of (future) solar cell technologies. The objective of the study is to identify potential bottlenecks for each technology and to formulate ensuing recommendations with regard to photovoltaic R&D policy in the Netherlands. In the study the potential environmental affects of PV modules are investigated for their entire life-cycle, that is from raw materials mining through module production and utilization to module decommissioning and, if possible, recycling.

In this report we will study multicrystalline silicon PV modules. Neither thin film multicrystalline silicon modules nor monocrystalline silicon modules will be discussed. In previous studies similar assessments have been made on cadmium telluride/copper-indium selenide modules [22] and amorphous silicon modules [5].

In this type of environmental assessment the energy and material flows for the entire life-cycle of a certain product are surveyed and analyzed with special attention to possible environmental hazards. For this purpose the life-cycle is divided into a number of processes, each of which is described by the typical product input and output flow, energy input, secondary materials input, process yield, water and air emissions, solid waste production and the output of reusable (secondary) materials. By chaining a number of relevant processes it becomes possible to assess the total impact on the environment and the energy and raw materials requirements for the entire product life-cycle. A protocol for conducting environmental Life Cycle Assessment (LCA) studies has been outlined by Heyungs et al [53] of the Centre for Environmental Studies Leiden (CML). An elaboration and application of this so-called CML protocol with special focus on energy systems has been described by Van Brummelen et al. [16]. Because we have somewhat different objectives in our study and because of methodological difficulties when applying the protocol to future production technologies the CML methodology will be followed only loosely in the present study.

A major problem with this type of studies is that the development towards future (energy) technologies is not easy to predict so that major uncertainties in the technology assumptions are unavoidable. For this reason we have chosen to highlight the sensitivity analysis in our approach. We have defined three possible technology cases: a worst case, a base case and a best case. The worst case is chosen in such a way it represents a good estimate of the present state of production technology and environmental control measures. The base case is defined as the technology which will most probably be commercially available within 10 years. The best case represents an optimistic view on production technology available within the next ten to fifteen years.

A number of environmental impact and risk assessment studies have been carried out over the past years. In the United States the Brookhaven National Laboratory (Moskowitz et al)

conducted, and still conducts, health and safety studies for photovoltaic solar cell production [e.g. 33] but no recent work on (multi-) crystalline silicon technology is available from them. In Germany, the Forschungsstelle für Energiewirtschaft (FfE) in Munich has published a number of thorough studies on energy and material flows in the production process of silicon solar cells [13,14,15] which proved to be an invaluable source of detailed information for the present study. However the FfE study describes only production technologies which were in (near) commercial use in the late eighties. It therefore gives only little insight into effects of future production technologies. At our own institute, the department of Science, Technology and Society of the Utrecht University, in 1987 a review study was done of the opportunities and bottlenecks, including environmental aspects, of introducing solar cells in the Dutch electricity generating system [11].

The research presented in the this report aims to integrate the results of the studies mentioned above in the framework of the Life Cycle Assessment methodology and to provide insight into the effects of future production technology. The objective of our study is to identify opportunities and bottlenecks of the respective technologies with regard to environmental risks and, finally, to formulate recommendations with regard to the Dutch research program on multicrystalline silicon solar cells.

The structure of this report is as follows. In chapter 2 we will describe the structure of the multicrystalline silicon solar cell and the PV module. We will give a description of the life-cycle of the multicrystalline silicon PV module and the technological parameters of the different processes in the life-cycle are given for the three cases. In chapter 3 the results of the material flow calculation of the life-cycle are given and in chapter 4 we present the results of the energy analysis for the life-cycle of multicrystalline silicon solar cell modules. We conclude the report with a summary of the major conclusions and with recommendations with regard to research on multicrystalline silicon solar cells.

2. Case definitions and module life-cycle description

2.1 Introduction

A life-cycle assessment generally starts with the definition of the goal and the scope of the assessment to be undertaken. This comprises three elements: application determination, system definition and definition of the subject of the study: the functional unit [16].

The objectives of this study have already been described in the introduction. The system definition will be elaborated in chapters 3 and 4 because we will define different system boundaries for the materials flows and for the energy flows.

The third part of the goal and scope definition is the functional unit, which is a description of the product (or the function of the product) under study and the quantity in which this will be represented.

In this report we define the functional unit as $1 \text{ m}^2 \text{ cell area}^*$ of multicrystalline silicon solar cell modules manufactured in a commercial scale production plant.

As outlined before we will discern three cases for the solar cell production technology: the worst case, the base case and the best case. The definition of the worst case is derived from data about present day production technology [13,14,2,7]. Encapsulated cell efficiency** in this worst case is set at 13%, while 15 year is taken as the module life time. The base case solar cell technology is defined as the technology which is expected to be commercially available within the next ten years. The definition of the base case is based on industrial and governmental assessment studies and interviews with experts in the production field [23,24,30,35,39]. Encapsulated cell efficiency for this technology is 16% and module life time 25 years.

The best case is a combination of several ideas to improve multicrystalline solar cell technology, which are expected to become technically feasible within the next 10-15 years. These expectations are mostly derived from far term expectations mentioned in studies and interviews. Encapsulated cell efficiency for best case modules is assumed to be 18% and module life time has been increased to 30 years.

In this chapter we will first give a general description of the cell structure. Then a more detailed description of the multicrystalline silicon solar cell technology in the discerned cases will be given. The purpose and process technology of several process steps will be elucidated.

2.2 The multicrystalline silicon solar cell

In the beginning of solar cell technology crystalline silicon solar cells were made exclusively from monocrystalline silicon material. These single crystals can be made by drawing an ingot from a melt of electrical grade silicon (the Czochralsky process). The produced ingots are

* Note that this is different from the 1 m^2 module area considered in our previous studies [5,22]. Here 1 m^2 cell area is chosen since the packing factor (the fraction of cell area to module area) differs between the three discerned technology cases. If a functional unit of 1 m^2 module area was chosen it would make the comparison of the LCA results among the three cases more difficult (1 m^2 module area would then comprise different cell areas). Results can easily be converted to module area by division by the module packing factor.

** Efficiency of the cell as it is integrated in the module, i.e. incorporating losses introduced at module level (e.g. cover glass reflection).

sawed into wafers, which form the basis for solar cell manufacturing. Drawback of this process is the low throughput, which is determined by crystal growth rate. The low throughput results in high ingot costs.

In later years, when the demand for low cost cells for terrestrial applications grew, a number of companies developed multicrystalline silicon (m-Si, also called semicrystalline or polycrystalline silicon) as a cheaper wafer material for solar cells. Multicrystalline silicon is mostly produced by pouring molten silicon into a crucible, where it is left to cool off gradually and solidify. This results in a large block of m-Si, which is subsequently cut into ingots.

Multicrystalline silicon contains more impurities than monocrystalline silicon. Due to impurities and crystal or grain boundaries in m-Si, at which recombination of generated electrons and holes can occur, solar cell efficiency is lower than in monocrystalline solar cells. In order to minimize this decrease in cell efficiency a number of process steps have been introduced into the multicrystalline silicon solar cell manufacturing process. These process steps will be described in chapter 2.3.

The thickness of silicon wafers used for solar cells has steadily decreased over the past years. Reasons for this are that production costs of crystalline silicon solar cells heavily depend on silicon feedstock cost and, secondly, that cell efficiency can be increased with decreasing wafer thickness. Ten years ago 400-500 μ was a widely used wafer thickness. Nowadays a wafer thickness of 200-300 μ is considered to be rather standard.

At the front side of the wafer (the sun side) an n-type emitter layer is formed by indiffusion of phosphorus atoms. The emitter layer is generally less than 1 μm thick [1]. The front contact consists of very small fingerlike lines of metal, usually silver (Ag). Metal line width is usually 150 - 200 μ , and the lines are interconnected by wider busbars (2 mm).

The backside of the solar cell is formed by an uniform layer of aluminum and silver which acts as a contact layer and as a reflective coating. The front side of the cell is usually covered with an antireflective coating (ARC) to reduce the reflection of incident light at the solar cell surface.

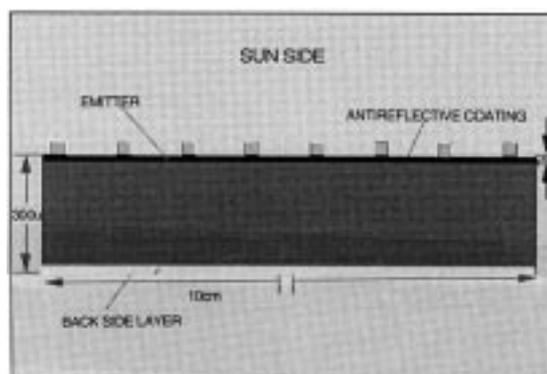


Figure 2.1: A schematic representation of a multicrystalline silicon solar cell (layer thicknesses not to scale).

2.3 The production of multicrystalline silicon solar cell modules

2.3.1 Mining and refining of silica

Raw materials for the production of silica (SiO_2) are quartz and sand. The mining of these materials and the subsequent reduction of silica to silicon is described by Van Engelenburg and Alsema [5] in their life-cycle assessment of amorphous silicon solar cell modules. The first part of the life-cycle of these modules (production of silicon) is identical to the first steps of the m-Si solar cell life-cycle.

The mining of quartz or sand is an established technology, which is widely used (not only for solar cell manufacturing), and which is not expected to change much in the future. Therefore the process characteristics for this step are assumed identical for all three cases.

Since sand is a very abundant material, raw material supply for silicon solar cells is not expected to become a problem whatever the future size of solar cell production.

After mining the sand is transported, classified, scrubbed, conditioned, flotated and deslimed. Emissions of these processes are negligible, except for the release of respirable dust containing about 17% of crystalline silica particles [33].

2.3.2 Reduction of silica to silicon

Silica can be reduced to silicon with carbon according to:



The carbon used in the reduction is supplied by charcoal, cokes, low ash coal and wood scrap. The resulting silicon is primarily used in the metallurgical industry and is thus called metallurgical grade silicon (mg-Si). The process yield is estimated at 80%. Releases from the silicon melt are CO, SiO, methane (CH₄), CO₂, and ethane (C₂H₆) [14]. Supplied with oxygen from the air, these substances react to respectively CO₂, H₂O, SiO₂ and NO_x. The remaining silicon-containing slag is sold as a by-product, while the emitted respirable silica particles are collected by a filter. The filter residue containing about 96.5% SiO₂ and 1.5% metaloxides is disposed of as solid waste [14].

After reduction of the Si has taken place oxygen is led through the melt to reduce aluminum and calcium impurities. Resulting purity of the mg-Si is 99.6% [5].

Because this very much an established technology we assume *worst and base case* process characteristics to be the same. In the *best case* silica reduction is integrated in the Si purification process (see below).

2.3.3 Production of high purity silicon

Metallurgical grade silicon still contains too many impurities to be used in either semiconductor or solar cell manufacturing. Semiconductor grade silicon (sg-Si; also called electronical grade, eg-Si) is usually produced with the Siemens process or derived processes. In the Siemens process mg-Si is hydrochlorinated to trichlorosilane (TCS, SiHCl₃), which is converted to eg-Si with hydrogen. The Siemens route results in high purity silicon (Si content > 99.99999% [9]), but is expensive and has a low yield. Because the degree of purity needed for silicon solar cells is somewhat lower than for integrated circuits, solar cell industries often use "scrap" material, i.e. material which does not fully meet the requirements of the semiconductor industry. This forms a relatively cheap source of raw material. With the expected increase in the production of silicon solar cells however, the use of scrap material may no longer be a viable option in the future. For this reason a number of manufacturers in the solar cell industry is looking for cheaper ways to produce silicon especially for solar cell production, the so-called Solar Grade silicon (sog-Si).

In the late seventies a solar-grade silicon purification process based on fluidized-bed technology was developed by the Union Carbide Corporation (UCC). This process was already described in our previous study on a-Si modules. Although a number of other

processes for sog-Si production have been developed in later years, we will take the UCC-route as the point of departure for the *worst and base case* technology in this study too*. In the UCC-process mg-Si is hydrogenated in a fluidized bed reactor (FBR) at 500°C and 3.5 MPa in the presence of a copper catalyst (2-4%) [17,18] according to:



A number of equilibrium reactions take place:



We see that the output of this process step is a mixture of (chloro-)silanes. The components of this mixture are separated by subsequent distillations. In the final distillation step pure silane is separated. In each distillation step the residue is fed back into the previous distillation unit. Because of the closed loop system only small amounts of waste gases are emitted. The releases that do occur, are led through a Ca(OH)_2 -scrubber, which converts them into CaCl_2 and SiO_2 [5], harmless substances from an environmental point of view.

In the final step of the process silane is pyrolysed in a FBR to sog-Si and hydrogen. The hydrogen gas is led back to the hydrogenation reactor. So all secondary input materials are produced by the process itself. Only small amounts of SiCl_4 and H_2 have to be added to make up for losses in the scrubber. The yield of the process is said to be near 100% [36]. In accordance with the assumptions in the a-Si study [5] we will assume a yield of 96% for the worst case and 98% for the base case.

For the *best case* silicon purification technology we assume other processes to become commercially available which does not need mg-Si as feedstock material and use less energy [23]. We will depart from a process based on the carbothermic reduction of high purity silica with high purity carbon, because of its low process energy requirement and thereby its potential for low production costs [21]. This route has been developed by, amongst others, Kawasaki Steel Corporation and Nippon Sheet Glass Co [26]. The actual process is similar to the reduction of silica to mg-silicon as described in section 2.3.2. The sog-Si process only uses feedstock materials of higher purity. Sand (of glass industry quality) is upgraded by flotation and acid treatment (hot HCl) which results in a silica content of 99.9%. The upgraded silica is converted into water glass (liquid glass) with dissolved impurities by melting with Na_2CO_3 . By treatment with acid, silica is precipitated and subsequently washed with acid and water, resulting in high purity silica (silica content > 99.999% [29]). For high purity carbon preparation we take the route described by Hagedorn [14], which uses hydrochloric acid (HCl) to purify carbon. The reduction of silica takes place in a closed furnace according to Aratani et al [26], which results in a higher yield and less impurities

* *The reasons for this choice are: 1) the UCC process is rather well-documented [17,18,33], in contrast to other, more recently developed sog-Si processes; 2) the same process was assumed in our study on amorphous silicon solar cell modules [5] and 3) it is a closed-loop process which has obvious environmental advantages. Drawbacks of this choice are: 1) the process has never been implemented on commercial scale, and 2) it is not fully representative of present-day commercial processes, especially with regard to its energy requirements (see further note on page 37).*

At present, the former UCC technology is used by Advanced Silicon Materials Inc. to produce silane. Also the technology is still under investigation on a pilot scale as a possible candidate for silicon feedstock production [94].

than conventional carbothermic reduction (impurities in the closed system < 1 ppmw, boron < 0.05 ppmw).

Goal of the present R&D is a yield of 90% and a process energy requirement (PER) of 20 kWh_t/kg sog-Si. Achieved results so far are 70-89% yield and an energy requirement of 40-50 kWh_t/kg sog-Si. Solar cell efficiencies of wafers produced in this process are comparable to conventional wafer efficiencies [26]. For our best case study we will assume a process yield of 80%, and a process energy requirement of 30 kWh_t/kg sog-Si produced.

2.3.4 Casting and sawing of silicon

The next step in solar cell production is the casting process in which high purity Si feedstock is converted into large blocks of multicrystalline Si.

The conventional approach is to melt the feedstock under an inert atmosphere (argon gas) and pour it into a graphite crucible in which it is allowed to solidify under controlled thermal conditions. For our *worst and base case* definitions we assume this casting technique to be used.

The multicrystalline silicon blocks (ingots) produced by conventional casting vary in size, depending on the size of the used crucible.

Due to the way the melt/solid interface moves through the meltstock most of the impurities are found in the outer parts of the ingot. Furthermore the grain sizes in these parts are substantially smaller than in the inner part of the m-Si. The presence of both impurities and a large number of grain boundaries (due to smaller grains) decrease solar cell efficiencies by facilitating recombination. For this reason the outer parts of the ingot are removed (contouring). After contouring the ingots are sawed into smaller blocks with a cross sectional area of 10x10 cm² in the worst case, resp. 12.5 x 12.5 cm² in the base case.

Due to enhanced casting methods, larger ingot sizes and higher quality feedstock the amount of m-Si lost in contouring and portioning has decreased from 45% [21] to about 15% [35] over the past years. For our worst case we will assume that about 30% of the material is cut off, which partly can be fed back into the melt. About half of the amount cut off (14% of the total amount of material) is assumed to be unrecoverable [35]. For the base case we assume that 20% of the material is cut off in contouring and portioning (11% of input material unrecoverable).

For the *best case* we assume another casting technique to be implemented: the so-called cold-crucible or electromagnetic casting process (see Figure 2.2). In the electromagnetic casting method the molten feedstock is not in contact with the crucible walls but it is contained by an electromagnetic confinement. RF-coils surrounding the crucible induce electrical currents in the vertical bodies, which on their turn give rise to a magnetic field in the crucible. The magnetic field in the feedstock causes a current in the molten silicon which is opposite to the coil current. The two opposite and thus repulsive currents lead to a confinement without crucible wall contact. At the bottom of the crucible a retractable support member is slowly withdrawn from the melt, while silicon is solidifying in moving away from the heated zone [25,37].

Advantage of this casting method is that no contaminations can enter the melt from the crucible wall. Furthermore the continuous character of the process permits casting of large size ingots and avoids the subsequent heating and cooling periods of conventional casting, thus reducing the energy consumption.

Application of the electromagnetic casting process is expected to lead to a further decrease in contouring and portioning losses: only 10% of the silicon material is discarded (of which 6% unrecoverable).

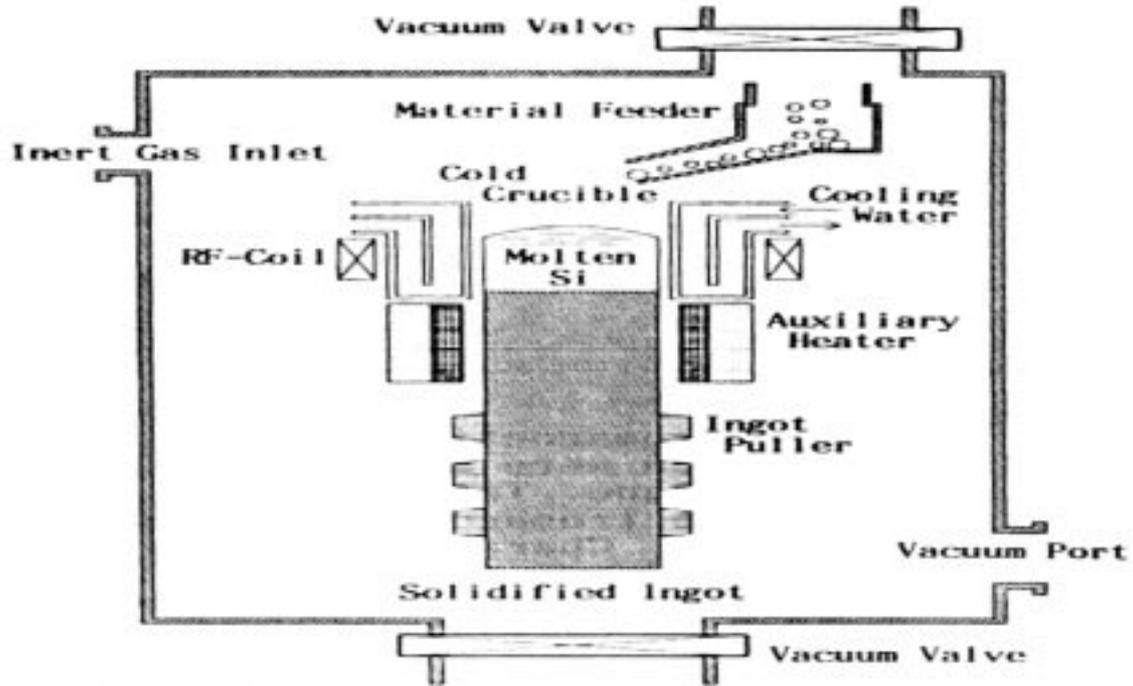


Figure 2.2: Apparatus used in electromagnetic casting [37]

After the casting, contouring and portioning we arrive at the wafering process in which the silicon blocks are cut into very thin slices. For this a multi wire saw (MWS) is generally used, combined with a slurry containing a cooling liquid and some abrasive particles like silicon carbide (SiC). Wire thickness has steadily decreased through the years [12,19,20] allowing a decrease of wafer thickness. In our study we will assume a wafer thickness of $300\ \mu$ in the worst case, $200\ \mu$ in the base case and $150\ \mu$ in the best case [52]. We assume a sawing loss of 50% for all cases (i.e. $300\ \mu$ in the worst case, $200\ \mu$ in the base case and $150\ \mu$ in the best case) [20].

Wafer size, on the other hand, is assumed to increase from $10 \times 10\ \text{cm}^2$ (worst) via $12.5 \times 12.5\ \text{cm}^2$ (base) to $15 \times 15\ \text{cm}^2$ (best case).

After sawing the wafers are cleaned, rinsed and dried. The silicon lost in sawing is discarded of together with the cooling liquid.

2.3.5 Etching and texturing

Before processing the wafers into solar cells the sawing damage has to be removed. This can be done by etching with sodium hydroxide (NaOH, 33% in water [9]). Subsequently the wafers are rinsed with water and concentrated sulphuric acid. Releases of H_2 , H_2O , Na_2SO_4 and Na_2SiO_3 (sodium silicate) will occur.



This NaOH-etch, assumed for the *worst case*, also partially texturizes the surface of the wafer. Texturizing results in a roughness of the surface, which causes a longer optical path for light which has entered the cell, thus increasing light absorption and solar cell efficiency.

In the *base case* a potassium hydroxide (KOH) etch will be used instead of the NaOH-etch. A KOH-solution gives a more complete texturing than a NaOH-solution.

In the *best case* we expect a process to be available, in which a two-step NaOH etch will be applied. In the first step sawing damage will be removed, while the second step results in a texture. The first step, which is close to the conventional damage etch, determines energy and material requirements. Therefore we will assume the same material and energy requirements per m² cell area as in the worst case (excluding batch size effects).

Table 2.1: Assumptions made for the cases regarding Si feedstock and wafer production.

process step	parameter	worst case	base case	best case
silica reduction	process	arc furnace	arc furnace	-
	process yield	80%	85%	-
high purity Si production	process	UCC	UCC	high purity Si reduction with high purity C
	process yield	96%	98%	80%
casting/ portioning	casting method	conventional casting	improved conventional casting	electromagnetic casting
	contouring losses	14%	11%	6%
wafering	wafer size	10 x 10 cm ²	12.5 x 12.5 cm ²	15 x 15 cm ²
	wafer thickness	300 μ	200 μ	150 μ
	wafering loss	300 μ	200 μ	150 μ

2.3.6 Emitter formation

In the next step the n-type emitter layer is formed in the wafer, usually by way of by in-diffusion of phosphorus atoms. For our *worst and base case* definition we take the POCl₃-process, in which nitrogen gas is led through liquid phosphoric oxychloride (POCl₃). The saturated nitrogen gas is passed over the wafers with oxygen in a diffusion oven at a temperature of 800-900°C.



The formed phosphoric pentoxide forms a layer of phosphorus-silica glass (SiO₂.P) on the wafers, from which phosphorus atoms will diffuse into the upper part of the wafer. After diffusion has taken place the remaining phosphorus-silica-glass layer is removed by etching with fluoric acid:



The third step in the emitter formation is the edge preparation. After the diffusion step the edges of the wafers also contain phosphorus atoms. In order to prevent short circuiting the

phosphorus-containing layers at the edges are etched off by way of a plasma etching process. In this process the wafers are placed in a plasma reactor where fluorine atoms are freed from CF_4 and react with silicon:



Emissions of the first step (reaction 7) are P_2O_5 and Cl_2 [14]. They are treated to form NaH_2PO_4 and NaOCl . In the second step (reaction 8) HF and H_2SiF_6 and in the third step SiF_4 and also some F_2 are formed (reaction 9). Subsequently these substances are treated to form SiO_2 , NaF and CaF_2 . Furthermore CO_2 and some fluoridized oil are released.

In our *best case* we expect the POCl_3 process to be replaced by a screenprinting process. In such a process a phosphorus containing paste is screenprinted on top of the cell. In a high temperature infra-red oven solvents are evaporated, the emitter is driven into the wafer and the oxide layer is fluidized to a passivating oxide. Etching of the phosphorus-silica-layer with HF will then no longer be necessary. Emission of NaOCl , NaH_2PO_4 , NaF and CaF_2 do not occur in the best case.

The edge preparation will take place mechanically (polishing for instance) in the best case. In this step about 0.5-1 μ of silicon is removed from the edges resulting in the emission of a very small amount of silicon dust.

2.3.7 Metallization

We assume contacts will be applied by screenprinting in all three cases. In the *worst and base case* an uniform layer of an aluminum and silver containing paste is first screenprinted on the backside of the cell. This layer provides a Back Surface Field (BSF) to prevent recombination of generated electrons and holes. The aluminum in this layer can also have a gettering effect. If the paste is fired at sufficiently high temperature, impurities in the silicon will be inactivated by the aluminum, thus increasing diffusion lengths of electrons and holes. For the front contact a silver containing paste is screenprinted in a fingerlike pattern. With regard to the metal line width a compromise has to be made between shadowing losses and series resistance [9]. The trend is towards smaller fingers. In present day technology (the worst case) line width is usually about 120 μ . In the base case we expect a line width of 90 μ , while best case line width is estimated at 50 μ .

In the choice of contact materials a compromise has to be made between costs and cell performance. Aluminum, which is attractive because of its low costs, can, however, not be used in front contact pastes. Aluminum dissolves the silicon in forming an Al/Si-alloy, and would thus destroy the emitter layer. The back side contact can contain aluminum. But because Al is not solderable still 80% of the metal in the back contact paste must be Ag.

Besides metals (Al and Ag, 70-80%) screenprinting pastes contain solvents, resins, fillers and glass frit. The solvents are added to adjust the viscosity of the paste in order to keep it printable. Resins keep the active particles in the paste (the metal particles) in emulsion. The glass frit is added to increase the cohesion between the metal particles and the adhesion between the metal and the wafer after screenprinting.

After the paste has been deposited the wafers are fired in a belt oven. Subsequently the cells pass a zone with a temperature up to 120-150°C, in which the solvents are evaporated, a 300-400°C zone, in which the resins are burnt, and a zone with temperatures over 600°C, in which the frit is sintered [8]. Emissions that occur during the firing process are evaporated solvents and burnt organic compounds [14].

In the *best case* we expect the conventional belt oven to be replaced by an infrared oven, which requires much less energy. Also we expect the gettering effect of the aluminum layer to be no longer necessary due to improved wafer quality. Due to technological progress we also expect problems with the solderability of aluminum to be solved so that the back contact can consist of Al. Furthermore the back contact is assumed to have a fingerlike pattern with an oxide layer for surface passivation between the metal fingers.

2.3.8 Passivation and antireflective coating

As pointed out before, defects, impurities and grain boundaries in the silicon material can reduce solar cell efficiencies by facilitating recombination of electrons and holes, generated in the semiconductor. Impurities can be inactivated by gettering as described in 2.3.7. Grain boundaries and defects are usually inactivated by bulk passivation (also called hydrogen passivation). In this process hydrogen atoms created in a plasma diffuse into the wafer to inactivate recombination centres.

The front surface is yet another facilitator of recombination processes. The recombination velocity here can be reduced by a surface passivation layer like SiO₂ or Si₃N₄.

Usage of a layer of silicon nitride has yet another advantage, since it can also act as an antireflective coating (ARC). Antireflective coatings can also be formed by TiO₂, Ta₂O₅ and several other substances.

In our study we assume the Plasma Enhanced Chemical Vapour Deposition (PECVD) of Si₃N₄ in *worst and base case*. This method has the advantage that besides surface passivation and antireflective coating the process also allows for hydrogen passivation. In the PECVD process the wafers are placed in a reaction chamber in which an electromagnetic discharge is maintained in an atmosphere consisting of silane (SiH₄) and ammonia (NH₃) diluted with nitrogen. At a temperature of 400-450°C the silane and ammonia react together to form a complex which is deposited on the wafers. Subsequently the hydrogen from this complex diffuses into the wafer, leaving a layer of Si₃N₄ on the surface.

In the *best case* we expect the quality of the silicon material to have improved to such an extent that hydrogen passivation will no longer be necessary. Titanium dioxide will then be used as an antireflective coating, applied by Chemical Vapour Deposition (CVD) of titanium isopropoxide (Ti[(CH₃)₂CHO]₄) according to:



The resulting water vapour is released into the air, the isopropanol is expected to be captured. A part of the titanium oxides (TiO_x) is discarded as a solid powder into the water, another part is discarded as solid waste [14].

The CVD process does not have a passivating effect, but merely introduces an ARC. Advantages of the CVD process over the PECVD process are a lower energy requirement (by a factor of 2) and lower occupational risks since the use of the highly explosive silane gas is avoided.

Table 2.2: Assumptions made for the technology cases with regard to cell processing.

process step	parameter	worst case	base case	best case
etching / texturing	sawing damage etchant	NaOH	KOH	NaOH
	texturing			NaOH
emitter formation	doping	POCl ₃ in diffusion oven	POCl ₃ in diffusion oven	screenprinted P in IR oven
	emitter back etch	-	HF/HNO ₃	-
	edge preparation	CF ₄ plasma	CF ₄ plasma	polishing
metallization	back contact layer	screenprinted Al/Ag	screenprinted Al/Ag	screenprinted Al
	back contact layer thick- ness	15 μ	10 μ	20 μ
	back side coverage factor	100%	100%	10%
	front side contact	screenprinted Ag	screenprinted Ag	screenprinted Ag
	front contact line width	120 μ	90 μ	50 μ
	front contact thickness	15 μ	10 μ	20 μ
	front side metal coverage	10%	7%	6%
passivation	bulk passivation/ surface passivation	PECVD of Si ₃ N ₄	PECVD of Si ₃ N ₄	-
antireflective coating		in passivation process	in passivation process	CVD of TiO ₂

2.3.8 Module assembly

After cell processing the solar cells will be tested. The yield of solar cell production is estimated at 95%, i.e. 5% of the tested cells are rejected.

Subsequently the remaining cells are encapsulated into a module. The modulation process is similar for the three cases, only module size and other process parameters will vary.

The tested cells are laid out in a module matrix and interconnected in four series using tin-coated copper strips. The tin layer is applied to enhance the solderability of the strips.

The next step is embedding the cell matrix (4 x 9 cells in worst and base case and 4 x 10 in the best case) in EVA foil. The encapsulation materials consists of a 3 mm thick sheet of chemically hardened glass, 0.5 mm EVA foil, the cell matrix, again 0.5 mm EVA foil, and 125 μ Tedlar/Al/Tedlar foil (50 μ aluminum layer) (Figure 2.3).

Subsequently lamination takes place at 120-150°C. The edges of the module are sealed with a polysulphide elastomer [14], and the modules are washed and dried. Finally a polyester junction box is attached, and if necessary the module is framed (usually with an aluminum frame).

In this study we will consider the energy and material balances of the frame separately from the module. So if a framed module is used, one can simply add the LCA results of the frame and the framing process to the results of the module itself.

Finally the modules are tested electrically. Refused modules can be cut into pieces, and the separate cells can be used in consumer electronics [5]. We assume 1% of the modules to be rejected.

Table 2.3 summarizes the assumed characteristics at module level, including cell efficiency and module life time (cf. 2.1).

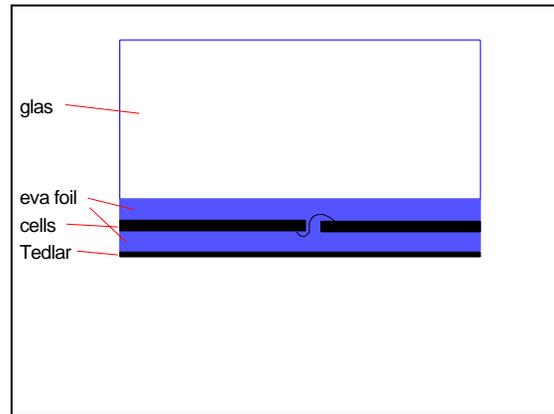


Figure 2.3: Module lay up

Table 2.3: Assumptions made for the discerned cases with regard to module characteristics.

process step	parameter	worst case	base case	best case
electr. testing	yield	95%	95%	95%
module production	cells/module	36	36	40
	glass sheet thickness	3 mm	3 mm	3 mm
	EVA foil thickness	2 x 0.5 mm	2 x 0.5 mm	2 x 0.25 mm
	Tedlar/Al/Tedlar thickness	125 μ	125 μ	125 μ
	module size (total)	0.44 m ²	0.65 m ²	1 m ²
module testing	yield	99%	99%	99%
encapsulated cell efficiency		13%	16%	18%
module life time		15 yr	25 yr	30 yr

2.4 Usage of the PV modules

During the period the PV modules are used for electricity production no emissions will normally occur. Only occasional washing of the top glass sheet could result in some emissions of e.g. water and detergents. We do not take these emissions into account in this study, because of their unpredictability (how often modules are washed, with what cleaning liquids, how much cleaning liquids, etc.). We also expect these emissions to be low compared to emissions occurring during the production of cells and modules.

Another possible cause of emissions during module use can be a fire, in which the module is exposed to high temperatures. This may result in emissions of CO₂ and burning products of EVA and Tedlar foils (possibly HF and HCl). No other significant emissions are to be expected in a fire. The emission of SiO₂ is not likely, since average fire conditions are too moderate to oxidize silicon. Fire-related emissions will not be considered further in this study.

2.5 Decommissioning and recycling

There have been few investigations on recycling options and other ways of handling used PV modules [4, 93]. The major problem with module recycling is the difficulty of separating the laminated module into its components, because of the cross-linked EVA polymers. Yet, it seems possible to dismantle old modules and to reuse the silicon in the wafers.

BP Solar, for instance, has investigated methods of liberating the wafers out of the EVA foil in order to re-use them [93]. This proved possible only by way of 25 hours soaking in HNO_3 . The recovered wafers could then be reprocessed into solar cells with a moderate performance. The costs of this method are fairly high (0.55 ECU/wafer) although less than normal wafer costs (≈ 1 ECU/W_p).

At this stage it is not clear whether methods such as described above can produce solar cells with sufficient performance or that silicon recycling will require remelting of the wafers followed by casting and sawing. In both cases a reduction of the energy requirements (due to omitted raw material production) is probable at the cost of some emissions of etching and/or cleaning fluids (used in removing and cleaning 'old' wafers).

Recycling of the module glass sheets by way of remelting may require removal of the EVA and Tedlar layers first, because glass containing more than 100 g of plastic per ton of glass is normally not accepted by glass recyclers. Recycling of module glass contaminated with plastics may be possible, however, if the glass is delivered batchwise so that can be processed separately [95].

The EVA polymers in a module are not recyclable at all since they are cross-linked.

The aluminum frame seems to be the only part which can easily be recycled. The energy gained by recycling the frame depends on the amount of energy required for upgrading the secondary material and on the fraction of secondary material used in frame production. The energy gain will, at the most, be equal to the energy requirement for raw material production.

In view of scarce knowledge on recycling possibilities (except the Al frame), energy and material requirements and environmental effects of recycling cannot be taken into account in this study. Therefore we will assume that the modules after removal of the frame, are disposed of as solid waste.

2.5 Conclusions

Three different cases have been outlined for the solar cell production technology, the worst case more-or-less represents present-day production technology, the base case describes technology which will most probably be commercially available within 10 years and the best case, finally, represents an optimistic view on production technology available within the next ten to fifteen years. The cell efficiencies assumed for these three technology cases are 13%, 16% and 18% respectively.

In the next two chapters we will assess the material flows and energy requirements for the three cases. This assessment will be focused at the production process of the solar cell modules, because: 1) the emissions from module usage (i.e. washing) are expected to be negligible and 2) processes and process data for module recycling are not yet available (with exception for the Al frame).

3. Material analysis

3.1 Introduction

In this chapter a description of the material flows for multicrystalline silicon solar cell modules will be given for the discerned technology cases. The processes involved have already been described in the previous chapter. Based on the choices made in chapter 2 and information obtained from experts in the field [3,23,24,30] the material requirements will be estimated per functional unit (= one square meter of cell area).

In our analysis only first order material flows will be accounted for, that is: all materials used in the production process of the solar cells itself, such as silicon, metals (silver, aluminum and copper), acids and alkalis (HF, HCl, H₂SO₄ and NaOH, KOH and their residues) and also bulk materials like glass and EVA.

Not considered here are materials which are used to produce commodities (like glass, copper and aluminum) or manufacture capital goods (machinery). Also the production of secondary energy carriers (e.g. cokes, electricity) is placed outside the (materials) system boundary (see figure 3.1).

We will analyze material requirements and the related emissions per process step as described in chapter 2. The worst case will be described explicitly. If no major differences exist between the assumptions made for the worst case and those made for base and best case we will refer to the tables and appendices for data concerning the latter. Point of departure for most calculations are material requirements and releases per kg feedstock, per wafer or per module. These data are given in appendix A. In section 3.10 these data are converted into material requirements and releases per m² cell area for easier comparison.

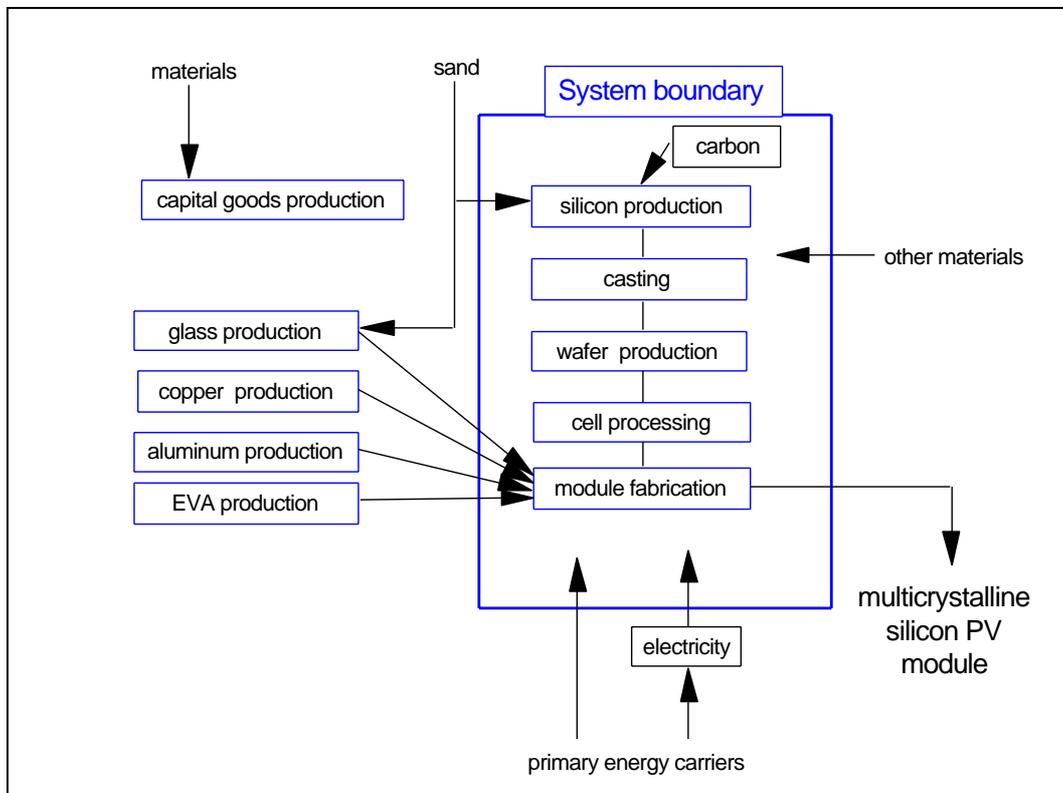


Figure 3.1: System boundary for material flow analysis.

3.2 Mining and refining of silica

The mining and refining of silica is the first step in producing multicrystalline silicon solar cells. To produce 1 kg of metallurgical grade silicon 2.8-2.9 kg of 98% SiO₂ (quartz) is needed [14,33]. In the best case the amount of SiO₂ required to produce 1 kg sog-Si can be calculated to be 2.67 kg. No other materials of environmental importance are used in the mining and refining process. The only emission occurring during the mining and refining processes worthwhile mentioning is the release of dust. Per kg of mg-Si produced the release of dust is estimated to be about 185 mg, of which 19 mg is respirable. The respirable particles contain about 17% crystalline silica [33].

Since silica mining and refining are considered to be mature and inexpensive technologies, we do not expect substantial improvements to be achieved in the base or best case with regard to process yield, emissions or energy requirements.

3.3 Reduction of silica to silicon

For the carbothermic reduction of silica as described in chapter 2.3.2 charcoal, Low Ash Coal, cokes and/or wood scrap can be used as a carbon source. Hagedorn [14] describes a mix of 0.4 kg charcoal, 0.6 kg Low Ash Coal, 0.4 kg cokes and 1.4 kg wood scrap needed for the production of 1 kg of mg-Si. During this process CO, SiO, CO₂ and C₂H₆ (ethane) are released. Supplied with oxygen they react to CO₂ (6.0 kg/kg mg-Si), H₂O (1.6 kg/kg mg-Si), SiO₂ (0.008 kg/kg mg-Si) and SO₂ (0.028 kg/kg mg-Si). After passing a filter these gases are emitted. The filter residue contains about 96.5% SiO₂, the rest consists of several metal oxides, silicon carbide and sulphate [14]. The filter residue is disposed of as solid waste. Silica-containing slag is sold as a by-product.*

In the *base case* we expect the process yield to be improved from 80% to 85% (see Table A.1 and A.2), while the production of mg-Si can be omitted in the *best case* (see chapter 2.3.3 and 3.4).

3.4 Production of high purity silicon

For the *worst and base case* production process for high purity silicon we take the process developed by Union Carbide Corporation for the production of polycrystalline silicon as point of departure.

In the Brookhaven report [33] the internal and external material flows in the UCC process are given at a process yield of 87%. According to van Swinnen [36] the present-day process yield is about 100%. For the worst case we assume a 96% conversion efficiency, for the base case 98%. This conversion efficiency is based on the total input of mg-Si. This means the amount of mg-Si needed to produce Silane Tetra Chloride (STC) is included**. The yield of the STC production process is not known, in our calculations we used a 100% yield.

* The values given by Hagedorn [14] are rather high. A study of the Brookhaven National Laboratory from 1980 [33] mentions the use of 1 kg cokes as carbon source, which would result in a CO₂-release of 2.9 kg (assuming a carbon content of 94% [34] and reaction yield of 80% [14]). Calculating the carbon requirement according to the stoichiometric equation (1) (chapter 2.3.2, the same assumptions) leads to a cokes requirement of 1.1 kg and a CO₂ release of 3.1 kg/kg mg-Si. In spite of this we will use the Hagedorn values for the worst case, since this study is the most thorough and explicit one.

** This in contrast with the process description in the Brookhaven report, see also chapter 2.

From the emission data given in the Brookhaven report the losses can be derived. For this study we assume the STC requirement to be equal to the losses in the process.* With these assumptions the material requirements of the production of high purity silicon can be calculated (assuming a proportional decrease of material requirements and emissions) to be 1.04 kg mg-Si and 0.15 kg Silane Tetra Chloride (STC) per kg eg-Si produced in the worst case.

The waste gases are led through a $\text{Ca}(\text{OH})_2$ -scrubber in which chlorosilanes are converted into CaCl_2 and SiO_2 [5]. Assuming a 100% conversion in the scrubber this would lead to the release of 0.19 kg CaCl_2 /kg eg-Si. The amount of H_2 lost is not even mentioned in the Brookhaven report, so we assume this release to be negligible from an environmental point of view. Other emissions in the worst case are 0.027 kg Si-powder and 0.052 kg SiO_2 per kg eg-Si produced. Data for the base case are listed in Tables A.1 and A.2 (Appendix A).

In the *best case* solar grade silicon (sog-Si) is produced by reduction of high purity silica with high purity carbon as described by Hagedorn [14]. The process includes the purification of silica and carbon with HCl. Another route is described by Aratani et al [26]. The most important difference with the process used in Hagedorn's study is the way the high purity carbon is prepared. The process mentioned by Aratani uses thermal cracking of propane as carbon source and has a present-day conversion yield of 70-80%. The route described by Hagedorn has a process yield of 65%. The higher yield in the Aratani route is caused by usage of an almost completely closed oven in contrast to the conventional oven used by Hagedorn. In this study we chose the Hagedorn route for carbon production because of the availability of data with regard to material requirement, emissions and indirect energy requirements. For the reduction step we assume the closed oven, described by Aratani et al, to be used, with an estimated process yield of 80%. With these assumptions material requirements can be calculated from Hagedorn. Per kg sog-Si an amount of 2.67 kg of silica (quartz) is needed. We do not expect the auxiliary materials and related emissions to decrease substantially with increasing process yield. Material requirements will therefore be: carbon, CaCO_3 , Na_2CO_3 , Al_2O_3 and HCl (20% solution). Calcium carbonate, sodium carbonate and aluminum oxide are used to produce glass fibres, which are subsequently leached with HCl. After waste treatment emissions are SiO_2 powder, CO_2 , CaCl_2 , NaCl, fluorine containing dust, chlorine containing dust and contaminated Si (cut of the edges of the block) [14]. The amounts of materials required and emissions released in this best case process are listed in Tables A.1 and A.2.

3.5 Casting of multicrystalline silicon ingots

Typical weight of a block of multicrystalline silicon produced by casting is 145 kg with the dimensions of $55 \times 55 \times 20 \text{ cm}^3$ [35]. This ingot is sawn into blocks with dimensions of $10 \times 10 \text{ cm}^2$. In our *worst case* the total weight of the remaining material is 100 kg. Of the 45 kg of silicon lost in contouring and portioning 25 kg is of high enough quality to be recycled as feedstock for the casting process.

Secondary materials used during the casting and sawing processes are argon gas and silicon nitride. According to Hukin (of Crystalox Ltd, a producer of casting furnaces) [35] 26 m^3 of

* *The required amounts of material mentioned in the Brookhaven report [33] are the amounts needed for the initial start up of the reaction. Once the reaction is taking place only small amounts of STC have to be added to make up for the losses in the scrubber. The amount of eg-Si produced in the process is determined by the capacity of the installation and the operating time. Consequently the amount of STC required per kg of eg-Si produced depends on these parameters. For this reason we do not take the start-up amounts into consideration.*

argon gas is used in the casting of a 145 kg block of m-Si. The argon use per wafer can thus be calculated to be 6.40 g (assuming a waferable amount of m-Si of 100 kg, a wafer thickness of 300 μ , a 300 μ kerf loss, and a argon density of 1.78 g/l)*.

The used argon gas is vented out, without environmental consequences. Other emissions to air do not occur during this process step. The silicon dust suspended in water caused by the sawing of the blocks into ingots is filtered out before discharging the water [35].

In the *base case* we assume the amount of argon used per block to remain the same. Due to the decreasing wafer thickness (to 200 μ) and reduced contouring and portioning losses [35] (to 20%, of which 16 kg can be recycled) the amount of argon used per wafer will decrease to 5.75 g.

In the *best case* the electromagnetic casting can take place in an inert atmosphere or in vacuum. We assume the casting in the best case also to take place in argon gas. furthermore we assume only 10% of the cast material to be lost in contouring and portioning. Of this amount 8 kg is expected to be recyclable. The argon requirement is estimated at 5.52 g/wafer.

3.6 Sawing of multicrystalline ingots into wafers

In sawing the ingots into wafers we assume a relative kerf loss of 50% due to the thickness of the sawing blade. This means a loss of 300 μ or 6.9 g Si per wafer for the worst case. In the base case (wafer thickness = 200 μ , cell area = 12.5 x 12.5 cm²) the loss is 200 μ or 7.2 g Si per wafer. Wafer thickness in the best case is 150 μ , which results in a loss of 150 μ or 7.8 g per wafer (cell area 15 x 15 cm²). Due to contouring losses and kerf losses the total amount of silicon required for wafer production is 16.6 g/wafer in the worst case, 16.0 g/wafer in the base case and 16.3 g/wafer in the best case.

In the wafering process a slurry is used consisting of mineral oil and silicon carbide particles. The slurry is used to cool the blades and the silicon material. The silicon carbide is added for its abrasive character. These materials (including the 50% Si lost in wafering) are submitted as waste to a waste burning installation for chemical waste. Data concerning material requirements and releases are listed in Tables A.1 and A.2.

Subsequently the wafers are cleaned with cleaning fluids, tensides and formic acid (a total of 3.4 g/wafer) [14]. The same amounts of these materials (containing some silicon) are submitted to waste water treatment before discharging [14].

3.7 Cell processing

3.7.1 Damage etching and texturing

In our *worst case* etching is done with sodium hydroxide. Whisnant [32] mentions a requirement of 2.7 ml NaOH/wafer. With a NaOH density of 2.1 g/ml this would result in NaOH requirement of 5.8 g/wafer. This is comparable with the 6.7 g NaOH/wafer mentioned by others. For comparison Hagedorn describes the usage of the more effective etchant KOH. KOH requirement in his study is set at 8.3 g/wafer, of which 5.5 g/wafer is not used and has

* Hagedorn [14] gives an argon requirement of 18.3 g/wafer. The difference could partly be caused by the larger wafer thickness used in the Hagedorn study (thicker wafers means less wafers per ingot, and thus less wafers per amount of argon gas). Another possible explanation for the difference is the smaller blocks used in the Hagedorn report (40 x 40 x 30 cm³, 110 kg). Smaller blocks result in higher relative losses due to contouring and portioning into ingots (thus less wafers per block).

to be neutralized in waste water treatment. This means that effectively only 34% of the etchant is utilized. If we assume the same utilization factor for the NaOH etchant of the supplied 5.8 g NaOH per wafer only 2.0 g NaOH will be used for etching. This would result in 3.5 g NaOH per wafer to be neutralized. If neutralization is done with H₂SO₄ [9] resulting compounds are Na₂SO₄ (3.6 g per wafer) and H₂O, both harmless substances from environmental point of view (the amount of H₂SO₄ required can be calculated stoichiometrically to be 4.3 g/wafer).

In the *base case* wafer size is larger than in the worst case, so the amount of etchant used per wafer will increase. We assume a KOH etch in combination with a 65% HNO₃ solution to be used in order to enhance texturing.

In the *best case* texturing and etching will be done in a two-step etch process (using two different NaOH etchants and different process conditions). The damage etch (comparable to the damage etch in the worst case) is the predominant step with regard to energy and material requirements. We assume the amount of etchant to be used (due to larger wafers) to increase. The amount of etchant used per m² cell area (step 1 + 2) will be the same as the amount used in the worst case. In the best case neutralization of NaOH after etching and texturing will also be done with H₂SO₄.

3.7.2 Emitter formation

In the *worst and base case* the emitter is formed by passing POCl₃ saturated nitrogen gas over the wafers. Hagedorn mentions a use of 0.06 g POCl₃/wafer [14].*

The amount of phosphorus diffused into the wafer is so small (relatively) that it can be neglected. The POCl₃ used will be converted into P₂O₅ (0.03 g/wafer) and Cl₂ (0.04 g per wafer). After several gas and water treatments they are discharged into the hydrosphere as NaH₂PO₄ and NaOCl [14]. The oxide etch following emitter formation (see chapter 2.3.6) requires 1.1 g HF/wafer [14]**. According to Hagedorn emissions are 1.1 g HF/wafer, and 0.004 g H₂SiF₆/wafer [14]. Since the 1.1g HF used in the worst case is an abundance, we assume the HF requirement to remain 1.1 g/wafer in spite of increasing wafer size.

In the *base case* an extra step is added in which the emitter is etched back over 0.1μ using HF and HNO₃. The amount of materials used in this step is not known, but the etching distance is so small compared to the distance in damage etching, we choose to neglect the material requirements of this step. Modern HF/HNO₃ systems are almost completely closed [24], so hardly any releases will occur (including NO_x emissions). Emissions related to this step are therefore also neglected.

In the *best case* the amount of phosphorus in the screenprinting paste can be neglected. No HF is needed here for oxide removal. Therefore no emissions of NaF and CaF₂ will occur. It is not known whether any solvents are released.

* The Brookhaven study [33] reports a much lower POCl₃ requirement of $6 \cdot 10^{-5}$ g/wafer, calculated from a specific doping density. In this calculation a material utilization of 100% is assumed. Although the actual utilization factor is not known, a 100% utilization seems very unlikely. Others mention a use of 6 mg POCl₃/wafer, which is ten times less than Hagedorn [30]. Whisnant [32] describes another process in which liquid phosphorus is used as a dopant source. Based on the amount of phosphorus used in this process [32] the amount of POCl₃ required can be calculated to be in the same order of magnitude (0.05 g/wafer) as described in the Hagedorn study. For this reason we have chosen to use the values given by Hagedorn [14].

** Again the Whisnant [32] values are in the same order of magnitude, while Brookhaven [33] values are much lower.

After the emitter formation the edges of the wafers have to be etched in order to prevent short circuiting. In the *worst and base case* this is done with a CF_4 -plasma. This process requires 0.07 g CF_4 /wafer (10 x 10 cm²), resulting emissions are 0.05 g SiF_4 /wafer, 0.07 g F_2 /wafer and 0.01 g CO_2 /wafer [14]. Fluorine and SiF_4 are treated to form SiO_2 , NaF and CaF_2 . With increasing wafer size material requirement and releases are assumed to increase proportionally with increasing edge length.

In the *best case* edge preparation is done mechanically by polishing the edges, thus removing silicon over a distance of about 0.5-1 μ . Emissions will be restricted to silicon dust (about 5 mg/m² cell area which will be neglected).

3.7.3 Metallization

In metallization two different screenprinting pastes are used, one for the back side and one for the front side .

In the *worst and base case* a uniform layer of aluminum is printed on the back side of the cell to create a BSF and to enhance gettering. The aluminum is mixed with silver in order to improve solderability. The aluminum is applied by means of a paste containing 75% metal (e.g. silver and aluminum). According to Nijs at least 80% of the metals must be silver in order to be solderable and to provide good contact. We assume a silver content of 90% of the total metal content in the worst case and 80% in the base case. Other components of the paste are solvents, resins and fillers (20%) and glass frit (5%) [14].

In the worst case 0.50 g Al/Ag paste per wafer is used for the back metallization layer [14], while in the base case 0.78 g is used on the 12.5 x 12.5 cm² wafer.

In the *best case* we assume the uniform back side layer between wafer and contact to be no longer necessary. Furthermore a paste containing aluminium only is used for the formation of the back side contact (coverage factor 10%), requiring 0.13 g/wafer.

The area between the contact lines are covered with a passivating oxide. Which oxide will be used is not known, but probably it is a thermally grown oxide like SiO_2 . We do not expect the oxide formation to contribute substantially to the energy and material requirements, so we choose to neglect this step.

For the front side contacts a Ag paste is used containing 80% silver, 15% solvents, resins and fillers and 5% glass frit. In the worst case 0.10 g silver paste/wafer is needed (10% coverage factor). In the base case also 0.10 g/wafer is used (7% coverage factor), and in the best case 0.08 g/wafer is required (6% coverage factor).

Emissions occurring during the firing process are evaporated solvents (0.14 g terpeneol and dibutylphthalate per wafer [14]) and 0.03 g CO_2 and H_2O (from burnt organic components [14]) in the worst case. Emissions in the base case and in the best case can be found in Appendix A (Tables A.2) and Table 3.2.

3.7.4 Passivation and antireflective coating

In the *worst and base case* bulk passivation, surface passivation and antireflective coating is carried out by the PECVD of Si_3N_4 . Worst case material requirements are estimated to be

110 ml (or 0.08 g) NH_3 per wafer and 12 ml (or 0.02 g) SiH_4 /wafer*. The exhaust of the PECVD reactor will be connected with a silane burner, where excess silane is converted to SiO_2 and H_2O .

Material requirements for the application of a TiO_2 layer (AR coating) in the *best case* are estimated at 0.2 g isopropoxide/wafer. Furthermore nitrogen is used as a flow gas. We assume the same nitrogen requirement as in the PECVD process. Resulting emissions are expected to be 0.16 g isopropanol/wafer, which is captured and 0.02 g water vapour/wafer which is released into the air. Also TiO_x (TiO , TiO_2 and Ti_2O_3) is formed, of which 0.004 g/wafer is discharged into the waste water. Another 0.05 g/wafer is discarded of as solid waste.

3.8 Module assembly

Before the cells can be encapsulated they must be tested. We assume that 95% of the cells pass this test, while 5% is recycled or disposed of as solid waste. This yield is not expected to improve for base case and best case due to decreasing wafer thickness.

After testing the cells are interconnected, using tin-coated copper strips. Copper requirements are estimated to be 0.5 g per wafer [39]. In the worst case and the base case 18 g of interconnects (90% Cu, 10% Sn) per module is needed, while in the best case 20 g will be used per module.

At a module size of 0.44 m^2 (the worst case) and a encapsulating foil thickness of 0.5 mm 415 g of EVA is required per module (calculated from [14]). Hagedorn mentions a cutting loss of 4.7%, which means an additional 19 g of EVA is needed in the worst case. For the best case we assume an EVA foil of 0.25 mm thickness to be used [31].

For the front side coverage a sheet of 3 mm chemically hardened glass is employed. In the worst case this would result in a glass use of 3.1 kg/module (calculated from [14], comparable with [33]). A thinner sheet of glass will not be viable for future modules since increasing module size requires a higher glass strength.

The back cover of the module is formed by a Tedlar/Aluminum/Tedlar layer of 125 μ [39], in which the Al layer is about 50 μ thick [24]. This results in a Tedlar/Al/Tedlar use of 61 g [31] per module in the worst case including 0.06 g Al.

In the laminating furnace compounds like butylene, 2-propanon, 2-methylpropanol, 2-ethoxy-2-methylpropane, 2-methylbutanol-2 and tertairbutyl-isopentylperoxide are formed [14] and vented out. The amounts of these cross linking products produced are not known.

The optional frame is assumed to be made from an extruded aluminium profile. Typical material use for a present-day module is 350 g of aluminium per meter frame length [97]. Assuming module dimensions of 1 m x 0.44 m (9 x 4 cells) in the worst case 1.0 kg of aluminum is used per module. In the base case module dimensions are 1.20 m x 0.54 m resulting in 1.2 kg of aluminum, while best case module dimensions are 1.25 m x 0.80 m (8 cells x 5 cells) requiring 1.4 kg Al per module. The framed module is made air-tight using a polysulphide elastomer, 265 g/module in the worst case (calculated from [14]). About 8% of the (hardened) polysulphide is discharged of as solid waste.

* All together this provides about 17 mmoles of hydrogen per wafer. Kishore et al [27] mentions 150 ml SiH_4 and 20 ml NH_3 per 5 cells of 7.5 cm diameter. This results in the provision of about 13 mmoles of hydrogen per wafer, which is the same order of magnitude as the figure we estimated. In the process described by Kishore about 40x more silane and 3x more ammonia is supplied than needed for a 1000Å layer of Si_3N_4 . We assume the amount of source gases needed to be proportional to the surface area of the wafers. We expect the calculated amounts (per m^2) also to be sufficient for bulk passivation since in our cases increasing wafer size is accompanied by decreasing wafer thickness.

Finally a junction box (440 g of polyester) is attached to the module with 38 g of silicone adhesive. About 1 g of silicone adhesive is wasted as injection losses [14].

The yield of module production is assumed to be 99%, so 1% of the modules is damaged during processing or is rejected in the mouldle test. A module weighs about 4.1 kg (mainly glass), so per module 0.04 kg of solid waste out of rejected modules is formed. The rejection of 1% of the modules produced also results in an increase of the material requirement per m² of functioning module. Since the increase would only add 1% to the material requirements we have chosen to neglect the implications of module testing for material requirements.

3.9 Module usage and decommissioning

As indicated in chapter 2 the emissions during the period of usage of the module are neglected in this study. After their useful life we assume here that the modules will be disposed of as solid waste.

In general, the disposal of the m-Si modules as solid waste is not expected to be problematic for health or environment [15]. Silicon, glass and EVA are all non-toxic materials.

Still, the metal content of the module requires attention. The copper and silver concentration (Cu = 2-5 g/kg, Ag =0.4-5 g/kg) in the module stay only just below the threshold value (5 g/kg) for the category of "Dangerous Waste" ("Gevaarlijke Afvalstoffen") according to the Dutch environmental regulations [96]. Although the metals are contained in a well-encapsulated module, leaching out of the metals cannot be ruled not if the encapsulation has been damaged.

No specific data on emissions from the waste phase are available.

3.10 Results and discussion

3.10.1 Inventory list

Departing from the data in the previous sections we can now calculate the material requirements and the emissions per square meter module area. This is called the "inventory list" in LCA terminology.

Material requirements are described in Table 3.1, while emission data are given in Table 3.2 (in kg/m² cell area). Note that 1 m² of cell area corresponds with respectively 1.22 m², 1.16 m² and 1.11 m² of module area in the worst, base and best case.

Table 3.1: *Material requirements for the life cycle of multicrystalline silicon solar cell modules in kg/m² cell area*

material	process	worst	base	best
quartz	Si-production	5.16	3.12	2.03
charcoal	silica reduction	0.72	0.41	-
Low Ash Coal	silica reduction	1.09	0.61	-
cokes	silica reduction	0.72	0.41	-
wood scrap	silica reduction	2.54	1.45	-
Silane Tetra Chloride	high purity Si-production	0.25	0.078	-
high purity carbon	high purity Si-production	-	-	0.84

material	process	worst	base	best
HCl (20%)	high purity Si-production	-	-	43.0
Na ₂ CO ₃	high purity Si-production	-	-	0.69
CaCO ₃	high purity Si-production	-	-	1.29
Al ₂ O ₃	high purity Si-production	-	-	0.76
argon gas	casting	0.67	0.39	0.26
mineral oil	wafering	0.62	0.67	0.46
SiC	wafering	1.34	0.86	0.60
NaOH	etching/texturing	0.61	-	0.61
H ₂ SO ₄	etching/texturing	0.45	-	0.45
KOH	etching/texturing	-	0.87	-
HNO ₃	etching/texturing	-	0.042	-
POCl ₃	emitter formation	0.006	0.006	-
HF	emitter formation	0.12	0.074	-
CF ₄	emitter formation	0.007	0.006	-
Al/Ag-paste	metallization	0.053	0.053	-
Ag-paste	metallization	0.011	0.007	0.004
Al-paste	metallization	-	-	0.006
SiH ₄	passivation/ARC	0.002	0.002	-
NH ₃	passivation/ARC	0.009	0.009	-
N ₂	passivation/ARC	0.10	0.10	0.10
Ti[(CH ₃) ₂ CHO] ₄	ARC	-	-	0.009
Sn-coated Cu-strips	module assembly	0.050	0.032	0.022
EVA foil	module assembly	1.21	1.14	0.55
chem. hardened glass	module assembly	8.68	8.44	8.12
Tedlar/Al/Tedlar	module assembly	0.17	0.16	0.16
Al (in Tedlar)	module assembly	0.0002	0.0002	0.0002
polyester	module assembly	1.23	0.78	0.49
silicon adhesive	module assembly	0.11	0.068	0.042
aluminum	framing	2.8	2.1	1.6
polysulphide elastomer	framing	0.74	0.70	0.67

Table 3.2: Process *emissions* in the life cycle of multicrystalline silicon solar cell modules in kg/m² cell area.

emission	process	worst case	base case	best case
emissions to air:				
respirable dust	mining and refining	0.00003	0.00002	0.00001
CO ₂	-silica reduction	10.9	4.93	-
	-high purity Si-production	-	-	4.03
	-emitter formation	0.001	0.001	-
SO ₂	silica reduction	0.051	0.023	-
Si-powder	high purity Si-production	0.049	0.015	-
F containing dust	high purity Si-production	-	-	7.6 · 10 ⁻⁷
Cl containing dust	high purity Si-production	-	-	0.002
argon gas	casting	0.67	0.39	0.25
N ₂	passivation/ARC	0.10	0.104	0.104
isopropanol	ARC	-	-	0.007
H ₂ O	ARC	-	-	0.001
"solvents"	-metallization	0.015	0.010	0.002
	-emitter formation?	-	-	-
CO ₂ + H ₂ O	metallization	0.003	0.003	0.001
cross linking products	module assembly	p.m.	p.m.	p.m.
emissions to water:				
CaCl ₂	high purity Si-production	0.35	0.10	11.9
NaCl	high purity Si-production	-	-	0.76
Na ₂ SO ₄	etching/texturing	0.37	-	0.37
KCl	etching/texturing	-	0.77	-
NaNO ₃	etching/texturing	-	0.053	-
NaH ₂ PO ₄	emitter formation	0.004	0.004	0.004
NaOCl	emitter formation	0.006	0.006	-
NaF	emitter formation	0.025	0.016	-
TiO _x	ARC	-	-	0.0002
detergents	module cleaning	p.m.	p.m.	p.m.
solid waste:				
SiO ₂	-silica reduction	0.015	0.006	-
	-high purity Si-production	0.093	0.028	0.0008
contaminated Si	contouring	0.29	0.11	0.036
CaF ₂	emitter formation	0.22	0.14	-
TiO _x	ARC	-	-	0.002

emission	process	worst case	base case	best case
rejected cells (cells/m ²)	cell testing	5	3.2	2.2
EVA foil	module production	0.053	0.052	0.024
silicon adhesive	module production	0.003	0.002	0.001
polysulphide elastomer	framing	0.059	0.056	0.054
rejected modules	module testing	0.11	0.11	0.09
module waste	PV system decommissioning	12	10.8	9.4
other waste:				
Si (in mineral oil)	wafering	0.73	0.73	0.73
SiC	wafering	1.34	1.34	1.34
mineral oil	wafering	0.62	0.62	0.62

First we will now discuss the material requirements and emissions in general terms and compare the results for the three technology cases. Subsequently we will evaluate the environmental impacts and compare the emissions from m-Si modules with those of another energy production technology, i.c. coal-fired electricity production.

3.10.2 General discussion of the material requirements and emissions

Materials that dominate the material requirements are, as could be expected, the bulk materials like glass, EVA and aluminum. A consequence of this abundance is that future possibilities of recycling these materials will need consideration. Probably the module design has to be reconsidered in order to facilitate recycling of module components ('design for recycling').

Other materials that are required in relatively large amounts are the input materials for the carbothermic reduction, e.g. quartz and carbon sources (wood scrap, Low Ash Coal, etc.). This process step also contributes dominantly to the emissions that occur during the life-cycle of the PV module. The emissions of (non-energy-related) CO₂ and SO₂ are about 200 times larger than the values we found previously for amorphous silicon solar cell modules [5]. This is caused by a silica requirement for feedstock production which is about 200x larger for m-Si modules than for a-Si modules, which in turn is largely due to the 100-fold thicker Si layer in m-Si cells (150-300 µm for m-Si vs. 350-500nm for a-Si cells).

The trend towards thinner wafers in m-Si modules is advantageous in more than one way. Not only will thinner wafers require less feedstock material (and thus less process energy for feedstock production). Also the emissions of carbon dioxide and sulphur oxide will be reduced. Other possibilities of lowering the amount of SO₂ released are using low-sulphur-content carbon sources in silica reduction or desulphurization of flue gases.

Next to the carbothermic reduction of silica and the module production, also the wafering process has a rather high material requirement with regard to silicon carbide and mineral oil. Research efforts in this field are therefore directed at the possibilities of recycling the coolant and the abrasive particles.

Furthermore, in the best case the amount of HCl used for purifying starting materials is relatively large. Here another purification method or a more efficient use of HCl should be considered. Perhaps instead of neutralizing HCl with Ca(OH)₂ a closed system could be applied, in which the hydrochloric acid can be separated from impurities to be recycled.

Finally one can note that the material requirements and emission data for certain substances can differ to a large extent amongst the three discerned technology cases. These differences can largely be attributed to the decreasing wafer thickness, increasing wafer size and the introduction of new technologies.

3.10.2 Environmental impacts

The "inventory list" of required materials and emissions (tables 3.1. and 3.2) does not yet give much insight into the health and environmental impacts of the solar cell life cycle. For evaluating these impacts we will focus on the following impact categories [10]:

- resource depletion;
- global warming;
- acidification;
- occupational risks.

The discussion on global warming and acidification impacts will be postponed to chapter 4, where we can also take energy-related emissions of solar cell production into consideration.

A full evaluation of the impacts according to the CML method for LCA studies [53], which involves calculation of cumulative impact factors per impact category, is hardly possible in this case because for most emissions from table 3.2 no weighing factors have been defined. Therefore we can evaluate the process emissions only on a qualitative basis or by comparison with emissions from other sources.

In order to place the emission values somewhat into context we will compare the emissions of some materials per unit of produced energy for multicrystalline silicon PV modules on the one hand and a coal-fired electricity plant on the other hand.

Resource depletion

The main constituents of m-Si modules, glass, EVA and silicon, do not need any scarce resources to be produced. Although exact figures on the reserves of quartz sand, the feedstock material for silicon production, are not available it will be clear that even if only a very small fraction of the total sand reserves meets the specifications for silicon production, it can still be considered as an abundant material.

The only required material which is listed as scarce is silver [10]. The silver requirement of ca. 50 g/m² in the worst and base case corresponds to 0,38 g/Wp. If base case m-Si modules would have to contribute 5% of the current world electricity production, then their production would require about 30% of the current silver production (13.7 kton/y).

This indicates that the silver consumption deserves attention from a resource conservation point of view as well as from a cost perspective. In this respect it is encouraging that the silver requirements in our best case are more than a factor 10 lower than in the worst case. Also one should note that cell manufacturers already consider silver as incompatible with large-scale module production, be it from a cost viewpoint.

The use of copper, a moderately scarce resource, by m-Si modules will not contribute much to resource depletion, because the requirement for PV is low in comparison to total Cu production capacity and resources.

Process emissions

Environmentally relevant substances (with their impact category) which are released in the PV module's life-cycle are:

- fluoride (human toxicity)
- nitrate (human toxicity)

- SO₂ (human toxicity and acidification)
- CO₂ (global warming)
- isopropanol (human toxicity, photochemical ozone formation)
- "solvents" (photochemical ozone formation).

Also the release of respirable silica particles is of importance since respiratory intake of silica can cause the lung disease silicosis. However, silica particles can be removed effectively with present-day scrubber techniques, so releases of this kind do not have to be problematic.

The exact amount and chemical composition of the emitted solvents (from the metallization step) is not exactly known. Still, both with regard to occupational safety and photochemical ozone formation these emissions do require some attention.

During regular operation of a PV module production facility no CF₄ will be released. However, incidental releases (due to for instance equipment failure) may occur. Therefore it is notable that CF₄ has a very high global warming potential (3500-5300 compared to 1 for CO₂) [53], so (accidental) emissions of this gas should be avoided as much as possible.

The atmospheric emissions of fluorine and chlorine in the best case (Si purification process) can be put into perspective by comparison with the emissions of a coal-fired electricity plant (in the Netherlands about 30% of the electricity plants is coal-fired). This comparison is not made in order to give a judgement on either fossil fuel derived energy or solar energy. Such a comparison should include many more aspects than just F and Cl emissions during production. The reason we make the comparison is merely to get an idea of the order of magnitude of the emissions related to (best case) PV modules.

The atmospheric Cl- and F-emissions of a coal-fired power plant have been estimated at respectively 30,000 kg (Cl) and 8,300 kg (F) per TWh_e produced [51].

The F and Cl content of the emitted dust in PV module production is not known. In our calculation we assume the emitted dust to consist of 100% of chlorine respectively fluorine. For supplying 1 TWh_e by best case m-Si modules in the Dutch climate about 217,000 m² of PV modules are needed (calculated over the life time of the modules, cf. table 4.4). This results in atmospheric emissions of 430 kg/TWh_e of chlorine and 0.16 kg/TWh_e of fluorine, amounts which are negligible when compared to coal-fired plant emissions (see table 3.3).

The water-borne emissions of fluorine and chlorine contribute to the human toxicity impact. However a coal-fired electricity plant also releases F and Cl in its waste water. According to Van Baardwijk [50] emissions are about 265,000 kg Cl/TWh_e and 8,000 kg F/TWh_e (600 MW plant, 5700 full load hours). For multicrystalline silicon PV modules these emissions are about 89,000 kg Cl/TWh_e and 1,800 kg F/TWh_e in the base case*.

Finally it can be noted that the silica emissions from PV module production are completely negligible to the silica emissions of a coal-fired plant.

As can be seen in Table 3.3 emissions due to electricity delivered by multicrystalline silicon PV modules are in most cases completely negligible compared to the amounts emitted by electricity generated with coal. Only fluorine and chlorine emissions to water are, although lower than for a coal fired power plant, too substantial to be neglected.

Table 3.3: Environmentally relevant emissions of m-Si PV modules (base/best case) compared to a coal fired power plant (in kg per TWh_e).

emission	released to	coal-fired electr. plant	m-Si PV module
F	air	8,300	0.16*
	water	8,000	1,800
Cl	air	30,000	430*
	water	265,000	89,000
SiO ₂	air	1,700,000-6,400,000**	0.7

Occupational health

For the occupational health, no serious problems are expected. Some of the used materials have to be treated with caution, e.g. etchants, acids, etcetera. A report on occupational health risks of photovoltaic industry by the Brookhaven National Laboratory [33] mentions dermal contact with chlorosilanes, HCl and HNO₃ and inhalation of HF and HNO₃ as a moderate acute hazard on workers in crystalline silicon solar cell industries. Dermal contact with HF is considered to be a high acute hazard. Exposure to HF and silane is considered to be a moderate chronic risk. Other materials are expected to pose no or low hazards on workers in crystalline silicon PV industry.

We expect the hazards of these substances to be controllable within the safety measures usually employed in chemical industries.

For incidental releases some extra safety measures may have to be taken. Releases of ammonia (MAC^{***} = 18 mg/m³), carbon monoxide (MAC = 29 mg/m³), respirable silicon dust (MAC = 10 mg/m³), silane (MAC = 0.7 mg/m³) and respirable crystalline silica (0.15 mg/m³) can create nuisance or hazards on the work force.

3.11 Conclusions

The material balance of m-Si modules is dominated by the bulk materials used for module encapsulation, such as glass, EVA, aluminium. It is therefore unfortunate that recycling of these materials (with exception for Al) seems rather difficult. The weather-resistant encapsulation of the modules is also a major bottleneck for the reuse or recycling of the silicon wafers. Reconsideration of the module encapsulation design in view of future material recycling and waste reduction possibilities is therefore recommendable.

A related point of concern are the contact metals used in m-Si modules. The silver content (and the copper content) of the worst case module stays only just below the threshold for "dangerous waste" according to current Dutch environmental regulations. Moreover, the silver requirements of the worst and base case module could form a major contribution to the depletion of silver resources if these modules would be deployed on a large scale: a PV

* These emissions only occur in the best case. The value given is a maximum, assuming a 100% halogen content.

** Assuming a SiO₂-content of fly ash of 60% [91] and an emission of 4-15 kg of fly ash per TJ of fuel input [94].

*** Maximum Accepted Concentration a limit for occupational exposure to dangerous materials [55].

contribution of 5% of the current world electricity production would require about 50% of the current silver production.

Emissions of (non-energy-related) CO₂ and SO₂ from m-Si module production are mainly caused by the carbothermic silica reduction process. Most other process emissions seem relatively small and will have little or negligible environmental impact. Possible exceptions are the water-borne Cl- and F-emissions of the worst and base case cel production process, which - on an energy basis - may be of the order of 20-25% of the equivalent emissions of a coal fired electricity plant.

Some attention may be necessary for emission of solvents or other volatile organic compounds from various process steps, among others from metal paste firing and - possibly - module lamination. These emissions will depend highly on processing conditions. Also care should be taken to prevent accidental emissions of CF₄, a gas with a very high Global Warming Potential.

4. Energy Analysis

4.1 Introduction

In this chapter an energy analysis is given for the total life-cycle of a multicrystalline silicon solar cell module.

Energy requirements will be given as the Gross Energy Requirement (GER). The GER of a certain product includes the Process Energy Requirement (PER) of all the processes needed to manufacture the product and the energy needed for material production. Also the heating values of the input materials are included, as is the GER capital, the amount of energy required to produce capital goods. The energy for transportation, however, will be neglected. According to Van Engelenburg et al this will lead to an underestimation of less than a few percent [5].

In describing the Process Energy Requirement the direct PER and the indirect PER can be discerned. The indirect PER (e.g. heating and lighting of a plant) is treated separately where possible, because of the large uncertainties that exist in the estimations for the indirect energy requirement due its plant design dependency.

We will describe the energy requirements of the discerned process steps for silicon production and solar cell manufacturing and the gross energy requirement of bulk materials like glass, aluminum, copper and EVA. Note that the system is defined differently than was done for the material analysis (see figure 4.1). In chapter 3 material balances for production of secondary input materials were not taken into account. Also material requirements of the production of capital goods were not included in the system boundary. For energy analysis more data concerning material and capital good production are available. Furthermore, the energy requirement for these two aspects is expected to be substantially.

For two reasons only the "bulk" materials, like glass, aluminium and EVA, among the secondary input materials are considered for their energy costs. Firstly, these bulk materials are expected to be the major constituents of the energy requirement for material production. Secondly, for many of the materials which are used in small amounts the energy required for production is not known. For the bulk material production a decrease of the energy requirements as a result of autonomous energy savings is assumed when going from the worst case to the best case.

The GER capital, the energy required for the production of capital goods such as production equipment, can of course not be estimated by us from detailed process analyses. Therefore these values will be estimated on the basis of statistical data presenting an average energy requirement per amount of money invested for different categories of capital goods. For this reason this energy requirement may also be called the energy requirement for investments. In our energy analysis we only consider the investments for installations and buildings.

Finally we will calculate the energy pay-back time for the investigated PV modules. Also a comparison will be made between the existing Dutch electricity supply system and electricity supplied by multicrystalline silicon modules with regard to energy-related emissions.

Throughout this chapter energy data will be given in kWh_e for electrical energy use and kWh_t (thermal) for the use of primary energy carriers.

4.2 Mining and refining of silica

During the mining and refining of silica very little energy is used. The amount of energy required depends on the distance between the mining area and the refining location. Also the

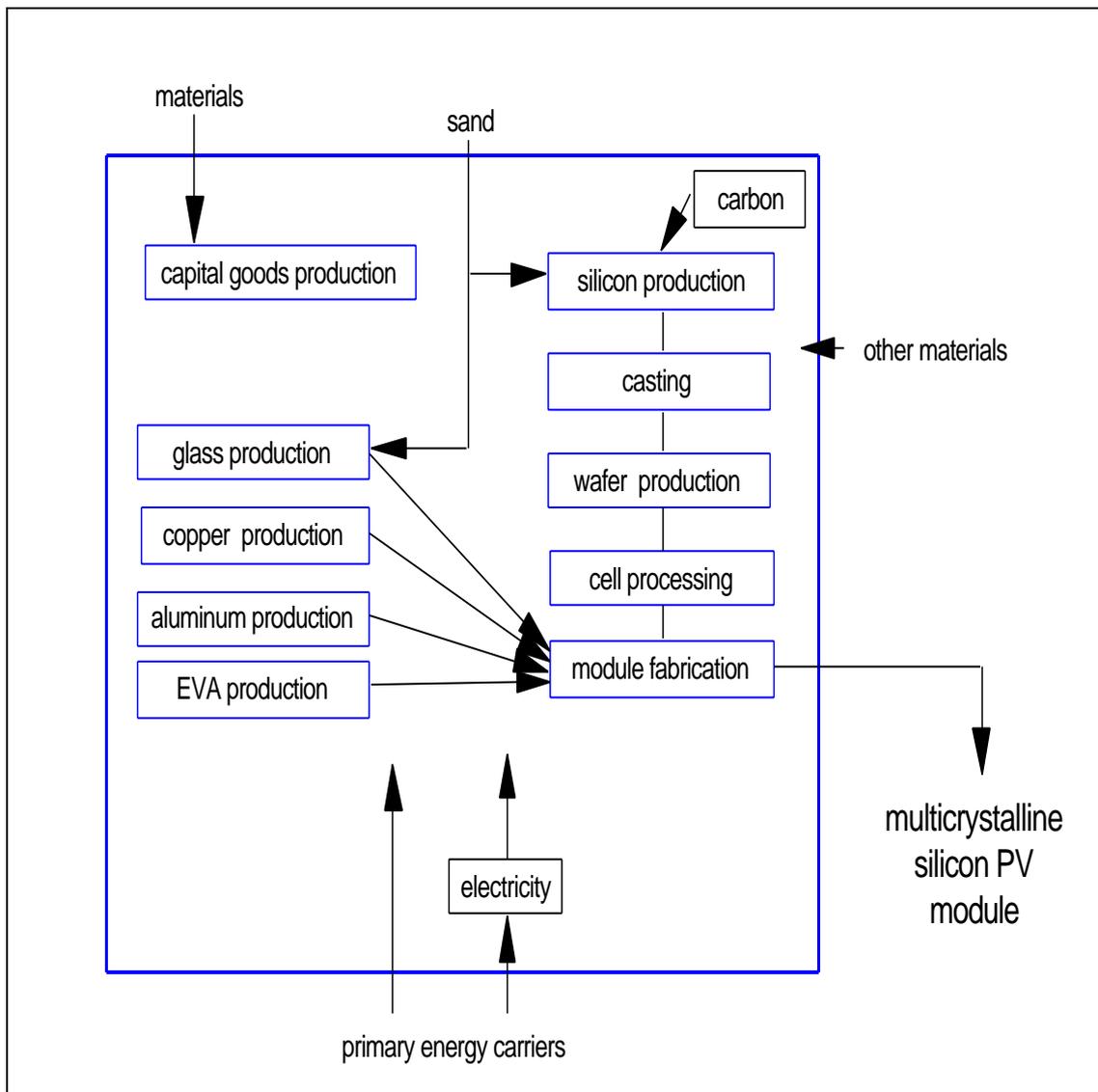


Figure 4.1: The system boundary for energy analysis

kind of mining site (below or above water level) is of influence on the energy requirement. According to Hagedorn [14] the energy requirement for mining and refining is less than 0.3% of the amount of energy used in the reduction of silica to silicon. This means an energy requirement of less than 0.2 kWh_t/kg of mg-Si produced. Since we do not expect this technique to undergo considerable changes, in this study we will use the same value for worst, base case and best case.

The indirect PER of mining and refining is expected to be very small and will therefore be neglected in this study. According to Hagedorn [13] also the energy requirement for capital investments is negligible.

4.3 Reduction of silica to silicon

In the Hagedorn study [14] an energy requirement is given for the reduction of silica to mg-Si of 51.34 kWh_t/kg mg-Si produced. The process energy requirement can be divided into direct process energy requirement (13.0 kWh_t/kg mg-Si) and indirect process energy (e.g.

heating and lighting of the plant, $0.89 \text{ kWh}_e/\text{kg mg-Si}$ ^{*}. The other constituent of the GER of mg-Si (Hagedorn neglects the energy requirement of mining) is the GER of the input products (carbon and carbon electrodes), which amounts to $11.40 \text{ kWh}_t/\text{kg mg-Si}$ [14]. This value will be used for the energy requirement in the worst case. According to the energy flow diagram given by Hagedorn in an earlier study [13] about 35% of the required energy is contained by the flue gases. We assume a part of this amount to be recovered in the future. Van Engelenburg et al expect an energy saving of about 18% in the base case, which would lead to a direct PER for mg-Si of $27 \text{ kWh}_t/\text{kg}$ and an indirect PER of $2.1 \text{ kWh}_t/\text{kg}$. In the best case the production of mg-Si is omitted (see chapter 2.3.3). The energy requirement for capital investments is expected to be negligible compared to the direct process energy requirement [13].

4.4 Production of high purity silicon

The UCC process for purification of silicon was reported to require 110 kWh_t of direct energy per kg eg-Si produced at a process yield of 85% [18]. For our *worst and base case* we set the process yield at the higher values of 96% respectively 98%. If we assume this yield improvement to be achievable without increasing the energy requirement and if we add of the energy requirement for the mg-Si to STC conversion (omitted in the original estimate, see also section 3.4), we arrive at a PER of eg-Si production of 108 kWh_t resp. 106 kWh_t per kg eg-Si produced for the worst and base case.

No data are available for the indirect process energy requirements of this process. In general, however, the indirect energy requirements for energy-intensive bulk processes are relatively small. Therefore we assumed them to be negligible for this process.

It should be noted that the above mentioned PER values for silicon purification are not representative for the more common Siemens process and that there is also some uncertainty about the exact PER value for the UCC process^{**}.

In our *best case* the production of high purity silicon takes place by reduction of high purity silica with high purity carbon. The expected process energy requirement is $30 \text{ kWh}_t/\text{kg sog-Si}$ produced (see chapter 2.3.3), while the energy requirement for the carbon used in the process amounts to $10.7 \text{ kWh}_t/\text{kg sog-Si}$ (cf. appendix B).

The total energy required for capital investments for high purity silicon production, casting and wafering is estimated at $0.03 \text{ kWh}_t/\text{wafer}$ [13] in all three cases.

* The values given by Hagedorn match well with those described by Häne et al [42]. Häne mentions a direct process energy of $13.5 \text{ kWh}_e/\text{kg mg-Si}$ and a indirect process energy of $0.89 \text{ kWh}_e/\text{kg mg-Si}$.

** PER values for the Siemens process are not reported explicitly anywhere, but they can be calculated from the Hagedorn [14] values for the GER of eg-Si and the GER of mg-Si to be about $215 \text{ kWh}_t/\text{kg eg-Si}$. The lower value for the UCC process seems reasonable because the UCC process was developed as a more energy- and material-efficient alternative for the Siemens process. The PER assumed here for the UCC process is also much lower than the value of $250\text{-}300 \text{ kWh}_t/\text{kg}$ assumed in our earlier a-Si study [16]. However, the latter value is much less reliable because it was calculated back from an assumed GER of silane. Also note that Lutwack reported a UCC PER value of 91 kWh [17], which is even lower than the value we use. Dawson (from Advanced Silicon Materials Inc., the current owner of the former UCC technology) confirmed to us that the value of 91 kWh per kg eg-Si is a good estimate for the UCC PER [94]. It is not clear, however, whether this 91 kWh refers to the final energy requirement or to the primary energy requirement (i.e. if conversion losses for electricity production were taken into account). Therefore we decided to use the value based on the process description by Breneman [18], a value which does represent the total primary energy requirement.

4.5 Casting, sawing and wafering

According to Hukin (Crystalox Ltd, [35]) it requires 1500 kWh_e to cast and 25 kWh_e to portion the amount of material used for about 7,250 wafers (145 kg including sawing losses, 10 kWh_e/kg)*. This results in a *worst case* energy requirement for casting and portioning of 0.21 kWh_e per wafer or 54 kWh_t per m² cell area. We do not expect the amount of energy required for casting and portioning to decrease substantially in the *base case*. The direct process energy requirement will therefore be estimated at 1525 kWh_e to produce 12.5 x 12.5 cm² ingots (for 8070 wafers). This results in a direct PER of 30 kWh_t/m² cell area.

In the *best case* electromagnetic casting will be implemented. Present-day (1990) direct process energy requirement for electromagnetic casting is 21 kWh_e/kg (22 x 22 cm² ingot on pilot plant scale). In the future we expect this to decrease below the level of conventional casting, since it is a continuous casting method. The energy requirement for heating the crucible in every cycle of the conventional method (which is lost during cooling off between two cycles) can be avoided. We therefore estimate a direct PER of 20 kWh_t/m² cell area for a fully developed commercial scale process.

The energy use for wafering is estimated by Palz & Zibetta at 20 kWh_t/m². We do not expect the energy requirement for the wafering process, expressed in kWh per m² cell surface, to decrease substantially in the future. (The PER per wafer, however, will decrease since wafer size increases.)

Therefore we will assume a direct PER of 20 kWh_t/m² for wafering in all three cases.**

4.6 Cell processing

Cell processing can be divided into process steps as was done in chapter 2 and 3. However the total (direct) process energy requirement for cell processing mentioned in several sources differs largely (from 24 kWh_t/m² cell area [21] to 344 kWh/m² [45]). It is not clear what causes these differences. One possible factor may be the fact whether the investigated plant is operated on a continuous basis (24 hours a day) or not. Also in some processes the batch size will influence the PER per wafer.

In the literature estimates for the PER of individual cell processing steps can be found [13,44], but in the light of the large differences mentioned above it does not seem useful to describe the energy requirements of the discerned steps separately.

On an indicative basis one can say that emitter formation and contact screenprinting together consume a major part of the process energy. Edge preparation and the PECVD of silicon nitride are somewhat less dominant.

* This is comparable with the 28 kWh_t/kg given by Palz and Zibetta [21]. We will use Hukin's data since it is more recent.

** Hagedorn [14] does not specify energy requirements for casting, portioning, wafering and cleaning separately, only a total energy requirement for these steps is given of 3.7 kWh_t/wafer. This is much higher than the sum of the process energy requirements given by others. Palz & Zibetta mention 0.8 kWh_t/wafer for casting (0.32 kWh_t/wafer), portioning and wafering (0.20 kWh_t/wafer), for 210 μ wafers and a kerf loss of 190 μ. Strese et al [44] give a process energy requirement of 1.5 kWh_t/wafer (1.0 kWh_t/wafer for casting, 0.07 kWh_t/wafer for portioning, 0.3 for wafering and 0.2 kWh_t/wafer for packaging). Wafer thickness is 450 μ, kerf loss 320 μ. The energy requirement per wafer for casting and portioning is dependent on wafer thickness, the energy requirement per wafer for wafering and packaging is not. Therefore values of Palz & Zibetta and Strese et al are comparable. We have chosen to use the Palz & Zibetta value for wafering, since no details are available about the assumptions made by Strese et al. For indirect process energy requirement and energy requirement for capital investments we have used the Hagedorn values, since no other data are available.

According to Hagedorn [13,14] direct process energy for cell processing (including cell testing) is 0.9 kWh_e per wafer (2.3 kWh_t/wafer). The route described by Hagedorn uses hydrogen passivation and a separate step for applying an antireflective coating (vacuum deposition). In our study we use the PECVD process for the combined passivation and antireflective coating for worst case and base case. Applying a hydrogen plasma as done by Hagedorn or a SiH₄/NH₃ plasma as we assume will require about the same amount of direct process energy. By correcting the value given by Hagedorn [13] for the omission of the vacuum deposition step, we obtain a *worst case* direct PER value of 0.6 kWh_e/wafer.*

In *base and best* case we expect this energy requirement to be reduced. Part of the reduction is expected to be accomplished by increasing batch size and a more continuous plant operation. Other contributions to the assumed decrease in energy requirement are due to the expected introduction of new technologies and installations. Using an infrared oven instead of a conventional oven for instance is expected to decrease the energy requirement of screenprinting by almost a factor eight. Other changes in process technology are mechanical edge preparation in the best case, where a fluorine plasma etch was used in worst and base case and a different way of emitter formation. Also the substitution of the PECVD process by a CVD process in the best case decreases energy consumption. This leads to an estimated energy requirement of 0.22 kWh_e/wafer in the base case and 0.18 kWh_e/wafer in the best case (including cell testing).

In the worst case an indirect process energy of 0.6 kWh_e/wafer will be required [13], in the base case 0.2 kWh_e/wafer is assumed to be needed [13], and for the best case indirect process energy requirement is estimated at 0.1 kWh_e/wafer (extrapolated from [13]). Energy requirement for capital investments for cell processing is 156 kWh_t/m² cell area in the worst case, 39 kWh_t/m² in the base case [13] and 19 kWh_t/m² in the best case (extrapolated from [13]).

4.7 Module production

Before module production the cells are tested, but the energy requirement for this step has been included in the direct PER for cell processing (see above).

For module production direct process energy requirements for separate process steps (e.g. connecting, laminating and testing) mentioned in several sources also vary largely. Therefore we will give one value for the direct process energy required for module production, except for framing. We will use the value given by Hagedorn [13], 3.8 kWh_e/module for module production, for our worst case.** We do not expect the direct process energy requirement for encapsulation to become much less in the future.

* This amounts to about 167 kWh_t/m² cell area. Palz & Zibetta [21] mention a direct process energy requirement of 24 kWh_t/m² cell area, while Strese et al [44] assume 80 kWh_t/m² to be required in cell processing. The latter however have assumed a three-shift plant operation to be used, while Hagedorn employs only one shift. If we correct for the different number of shifts between Hagedorn and Strese, the values for the direct PER are comparable. Therefore we have chosen to use the (corrected) Hagedorn value in our report.

** This results in a direct energy requirement of 9.7 kWh_t/module in the worst case. Strese et al [44] mention a comparable process energy requirement of 9.0 kWh_t/module (without framing). Apparently scaling up does not influence modulation as it does cell processing. Palz & Zibetta [21] assume 17 kWh_t/m² module area (= 9.4 kWh_t/module) of process energy to be required for modulation.

According to Hagedorn [13] the direct process energy requirement for framing is negligible. De Vos [39] mentions an energy requirement for framing of 0.02 kWh_e/module. Therefore we chose to neglect the direct energy requirement of the framing process.

The indirect process energy requirement for module production is estimated at 6.2 kWh_t per - module in the worst case, 3.0 kWh_t/module in the base case [13] and 2.9 kWh_t/module in the best case (extrapolated from [13]). The energy for capital investments for module production is included in the capital investment energy requirement for cell processing (see chapter 4.6).

The secondary input materials* used in the module production process contribute substantially to the GER of the PV module, among which most notably the glass cover, the EVA foil and the (optional) aluminium frame (see table 4.2)**. Glass and EVA alone contribute about 10% to the total energy requirements of the worst case module.

The addition of an aluminium frame may add considerably to the energy requirement. Production of the 0.35 kg aluminium per meter frame length (=1 kg/module) would require almost 175 kWh_{th}/m² for worst case, that is 18% of the frameless module's GER. Actual framing requirements, however, will depend on the mounting method, for instance in roof-integrated systems the modules themselves are often frameless (but some light aluminium profiles are used as a support structure). In fact the material and energy requirements for the frame can best be considered in relation to the design of the array support structure, a subject which is outside the scope of this report.

4.8 Gross energy requirement for m-Si modules

In the preceding paragraphs the energy requirements of the discerned process steps and material production have been given. In tables 4.1-4.3 the cumulative energy requirement for m-Si modules is presented. The energy required for heating and lighting of the plants (indirect PER) is given separately, as is the gross energy requirement for the frame.

Note that the energy requirements per m² module area can be calculated by dividing the energy requirements per m² cell area by the module packing factor (resp. 0.82, 0.87 and 0.90 in the worst, base and best case).

We see that the GER for the worst case (frameless) module is almost 1000 kWh_{th}/m², but that a reduction to 40% or even 20% of this value seems possible for the future. About 30% of worst case GER is from indirect energy consumption, i.e. for heating, lighting etc. of the production facilities and for production of capital goods. It must be borne in mind that the estimates for these indirect energy requirements have a considerable margin of uncertainty.

* See Appendix B for a discussion of the Gross Energy Requirement of some secondary input materials like copper, aluminium and glass.

** The energy requirements mentioned above are somewhat different than those used by van Engelenburg et al in their study on a-Si solar cell modules. Differences are due to the fact that van Engelenburg uses gross energy requirement of raw aluminium instead of anodized aluminium profiles. Furthermore in the a-Si report the energy requirement of EVA foil is not taken into consideration, since no data were available at the time concerning the gross energy requirement. The gross energy requirement per kg of glass used also differs, since van Engelenburg et al use the value for packing glass instead of chemically hardened sheet glass. However, the higher energy requirement per kg is compensated by using glass with another density (thus more kg of glass per module). Based on our new estimates we expect the production of input products of an a-Si module to require an additional 25 kWh/m² cell area for EVA and another 21 kWh/kg aluminium used for the frame in the worst case.

Table 4.1: Direct process energy requirement for the production of m-Si modules (in kWh/m² cell area).

process step	worst case	base case	best case
mining and refining	0.4	0.2	0.2
silica reduction	60	29	0
hp-Si production	188	111	23
casting/portioning	54	30	20
wafering	20	20	20
cell processing (inc. cell testing)	162	35	19
module production (excl. framing)	27	16	9
total	511	241	91

Table 4.2: Energy requirements of secondary input materials for m-Si solar cells (in kWh/m² cell area).

Material	worst case	base case	best case
carbon ¹	21	12	8
Cu strip	1.4	0.8	0.5
EVA foil	25	22	10
chem. hardened glass	36	31	27
Tedlar	5.4	4.7	4.2
total materials (excl. frame)	89	70	50
aluminum	175	120	80

1) Carbon input comes from different carbon sources (charcoal, coal, etc.) in worst and base case.

Table 4.3: Gross energy requirement for m-Si modules (in kWh/m² cell area)

	worst case	base case	best case
Process Energy Requirement - direct	511	244	91
Process Energy Requirement - indirect	210	46	19
Gross Energy Requirement for secondary input materials (glass, EVA, etc.)	89	70	50
Gross Energy Requirement for investments	160	40	20
Total Gross Energy Requirement (excl. frame)	970	400	180
Gross Energy Requirement of frame	175	120	80

4.9 Energy pay-back time of m-Si solar cell modules

To place the calculated figures into perspective the energy pay-back time for a multicrystalline silicon solar cell module as described in the discerned cases will be calculated. The energy pay-back time (EPBT) is the time the module has to function to produce as much electricity as was needed for producing the module.

In the energy pay-back time calculations we have assumed an improvement in conversion efficiency of electricity generation for base and best case. In the worst case this conversion efficiency is set at 39%, in the base case at 42%, while in the best case a conversion efficiency of 45% is assumed [5].

The global mean solar irradiation is about 1700 kWh/m² per year, while the Dutch mean irradiation is about 1000 kWh/m² per year [5]. The conversion efficiency of the module is 13% in the worst case, 16% in the base case and 18% in the best case. For the yearly Performance Ratio* of the total solar energy system we take a worst case value of 0.75, reflecting the present state-of-the-art for a grid-connected PV system. The PR is increased to 0.80 resp. 0.85 for the base and best case to reflect enhanced system technology.

Table 4.4: Energy production data and energy pay-back time of m-Si solar cell modules for the discerned cases for global average (1700 kWh/m²) and Dutch (1000 kWh/m²) irradiation conditions.

			worst case	base case	best case
	solar cell efficiency	%	13	16	18
	Performance Ratio of PV system		0.75	0.80	0.85
Global average	electricity generated	kWh _e /m ² .yr	166	218	260
	primary energy saved	kWh _f /m ² .yr	425	518	578
	energy pay back time	yr	2.3	0.8	0.3
	extra EPBT for frame	yr	0.4	0.2	0.14
	electricity generated over module life	kWh/m ²	2,490	5,450	7,800
The Netherlands	electricity generated	kWh _e /m ² .yr	98	128	153
	fossil energy saved	kWh _f /m ² .yr	250	305	340
	energy pay back time	yr	3.8	1.3	0.5
	extra EPBT for frame	yr	0.7	0.4	0.2
	electricity generated over module life	kWh/m ²	1,470	3,200	4,590

* The Performance Ratio (PR) is defined as: $(E_{ac} * G_{STC}) / (E_{irr} * P_{sys})$
 where E_{ac} = the AC output energy (kWh) and E_{irr} = the total irradiation (kWh/m²), both accumulated over a certain period; G_{STC} = the STC irradiation (=1 kW/m²) and P_{sys} = the nominal power rating of the system.
 The PR is a measure for the average performance of the PV system in its entirety, taking into account losses for non-STC irradiation, mismatch, tracking, temperature, cabling and dc/ac conversion.

4.10 Energy-related emissions

The production of the energy required for solar cell manufacturing will lead to emissions which should be considered in addition to the process emissions discussed in chapter 3. We will restrict our evaluation of these energy-related emissions to CO₂, SO₂ and NO_x.

For determining the energy-related emissions it is of importance what kind of energy source is used (because of the varying carbon and sulphur content of different sources). The distinction between electrical energy and fuel energy cannot be made for all the energy requirements mentioned in this chapter. From Hagedorn [6,13] it can be derived that about 28% of the gross energy requirement of a multicrystalline silicon solar cell module is delivered by fuel energy. For future developments the relative fuel energy part is expected to increase to 32% (the electricity demand decreases stronger than the fuel requirement^{*}). If we apply this figure to the gross energy requirement we calculated (28% fuel energy requirement in the worst case, 32% in the base case and 34% in the best case) we can calculate the CO₂, SO₂ and NO_x emissions related to fuel energy use. Since the type of fuel used is not known, we use the generic emission data recommended by Van Engelenburg et al. in [10] representing averages of the emission data for coal, natural gas, fuel oil and refinery gas.

The remaining, non-fuel part of the gross energy requirement is assumed to be electrical energy. To calculate the emissions resulting from this electrical energy use we will use the emission data of the existing Dutch electricity supply system [41] (for all three cases the same).

The results for the total energy-related emissions are given in table 4.5, expressed as kg emission per GWh of electricity generated over the PV system life-time under Dutch irradiation conditions (resp. 15, 25, 30 years for the worst, base and best case). Comparison with the **non**-energy-related emissions of CO₂, SO₂ from table 3.2 (after converting them to kg/GWh) learns that the latter are at least one magnitude smaller, so that they can readily be neglected.

Table 4.5 also presents the resulting impact factors of Global Warming Potential (GWP) and Acidification Potential (AP). GWP represents the accumulated greenhouse gas emission in CO₂-equivalents (trivial in this case), while the AP gives the accumulated acid emission in SO₂ equivalents (weighing factor for NO_x = 0.7) [10].

Now we can compare the energy-related emissions of PV modules and of the average Dutch electricity supply. This comparison is made merely to place the emissions from PV into perspective. We have to take into account that the emissions mentioned for the average electricity supply system are direct emissions, e.g. released during energy generating. Emissions during material production, plant construction, etc. are not included (but these indirect emissions are generally small for conventional plants). The emissions for PV modules on the other hand are all indirect, i.c. stemming from material and module production.

We can see that even worst case emissions for PV are a factor 3-4 lower than for the average Dutch electricity supply. In the base and best case these factors increase to more than a factor 10 resp. 50.

^{*} *Increasing batch size and more continuous plant operation is expected to have a bigger influence on the energy requirement for the cell processing than on the energy requirement for bulk processes like silica reduction and silicon purification. The use of fuel occurs mainly in the bulk processes, so overall fuel requirement is not expected to decrease as much as overall electricity requirement. Furthermore, technological changes (e.g. more energy efficient equipment) are expected to be implemented more often in cell processing steps than in bulk processes.*

Table 4.5: Energy-related emissions and primary energy requirement for m-Si modules compared to the average Dutch electricity supply system. Also Acidification Potential (SO_2 equivalents) is given, the value of the Global Warming Potential (CO_2 equivalents) is equal to the CO_2 emission value.

emission of:	PV worst case	PV base case	PV best case	average Dutch electricity supply
CO2 (kg/GWh _e) (= GWP)	167,000	31,000	9,800	666,000
SO2 (kg/GWh _e)	315	58	18	870
NOx (kg/GWh _e)	370	68	21	1,210
Acidification Potential (kg/GWh _e)	574	106	33	1,720
primary energy consumption (TJ _l)	2,400	450	140	9,000

4.11 Discussion

Our worst case estimate for the GER of m-Si modules is about two times lower than the value given by Hagedorn [13, 14] for "present-day" (i.c. 1988) technology. This is mainly due to our assumption of thinner wafers (300 μ vs 450 μ), another production route for high purity silicon (with a higher process yield and lower process energy requirement) and the availability of more recent data on energy requirements. These results are in line with expectations mentioned in earlier studies (Hunt, 1977 [49] and Aulich, 1985 [43]), where wafer thickness, kerf loss and the production of high purity silicon were considered to be the major opportunities for lowering the energy requirement of multicrystalline PV modules.

The estimate of 260 kWh_{th} per m² cell area* published by Palz and Zibetta [21] for modules based on 190 μ m wafers cannot be compared easily to our estimates because of the lack of detailed information in their publication (e.g. the energy requirement for the frame) and because of different assumptions. In view of their assumptions on silicon purification and wafer thickness their value should lie between our base and best case. However, if their module does indeed include an aluminium frame the energy remaining for the module itself might be estimated at some 140-180 kWh_{th}/m², which seems very low in comparison with our estimates. In our view the Palz and Zibetta estimate is too optimistic.

The direct process energy accounts for about half of the gross required energy. Dominating contributions to direct process energy requirements are the production of feedstock (production of mg- and eg-Si or sog-Si) and cell processing. With the assumptions made for the discerned cases the direct process energy requirement for these steps is expected to decrease from about 410 kWh_l/m² cell area in the worst case to 175 kWh_l/m² in the base case

* Palz and Zibetta give a value of 235 kWh_{th} per m² module area and a 0.9 cell/module area ratio. An aluminium frame is said to be included in this figure. For the GER of the silicon feedstock they assume a very low value of 20 kWh_{th}/kg based on the same carbo-thermic process we assume for our best case.

and 40 kWh/m² in the best case. Relative contributions are about 40% in the worst and base case, and only 20% in the best case.

The amount of energy required for material production is relatively low (if the aluminum frame is excluded), but its relative importance is increasing from worst to best case (from 9 to 28%), since expected energy savings for material production are less than for other parts of the PV module production.

The indirect process energy requirement and the energy required for investments are rather high, both 20% of the GER of the PV module (excluding the frame) in the worst case. In the base and best case both are expected to be about 10%. Note that these two contributions have a large uncertainty and are very much dependent on plant lay-out, etc.

The sulphur emissions from m-Si modules are substantially lower than for conventional electricity generation, for an energy source considered to be sustainable they are rather high, especially in the worst case. A reduction in SO₂ emissions could be achieved by using low sulphur fuels or desulphurization of flue gases, especially in the fuel-intensive processes, such as material and feedstock production and purification.

The calculated primary energy requirements and the emissions per amount of electricity generated are in the same order of magnitude as those found previously for amorphous silicon modules [5]. This is caused by the 2 times higher solar cell efficiency which compensates for the 2 times higher energy requirement of m-Si modules.

If aluminum is used for framing the module, this will increase the gross energy requirement substantially. An aluminum frame may add about 17% to the GER in the worst case and this might increase to 30% in the base case resp. 45% in the best case. However, frame requirements are very dependent on the mounting configuration.

Therefore an important aspect of future development should be to investigate the possibilities of using frameless modules or less energy intensive frames in conjunction with support structures with a good environmental profile. Sometimes plastic frames are mentioned as alternative for an aluminum frame, but we do not expect the gross energy requirement for a plastic frame to be substantially less than for an aluminium one.

A relatively simple way of reducing the energy required for framing the module is the input of secondary (recycled) aluminium. The gross energy requirement we calculated for the aluminum frame is based on 100% virgin material. The gross energy requirement of recycled aluminum is only 5-8 MJ/kg, (virgin aluminum is almost 200 MJ/kg). The energy requirement of extruding and anodizing will still be required. So if producing aluminum profiles out of 100% recycled aluminum would be feasible, gross energy requirement would be only 20% (45-48 MJ/kg of aluminum profile) of that for virgin material. It is possible that recycling of the aluminum leads to a weakening of the material and more aluminum has to be used per profile to maintain the strength. If this will be necessary and to what extent is not clear, but opportunities for reducing gross energy requirement are certainly there.

Input of secondary glass is another option to reduce the gross energy requirement of multicrystalline PV modules. This, however, is not expected to have a major impact on PV module energy requirement for several reasons. First, the gross energy requirement of 'new' glass is much less than that of 'new' aluminum (about 10 MJ/kg compared to 200 MJ/kg). Second, requirements set on glass sheets used in PV technology with regard to optical properties are rather strict, so the fraction of secondary glass that could be used would probably be rather low. Third, most energy used in glass production (about 80%) is used for

melting of the glass [38]. Even if much secondary glass is used, the melting energy will still have to be supplied.

Further measures to achieve reduction of the energy requirements may be the monitoring of direct and indirect process energy requirements, the scaling up of cell production processes (increasing batch sizes and more continuous plant operation) and the improvement of material utilization.

Finally we want to point out that our choice for the UCC process for eg-Si reduction has a substantial effect on the gross energy requirement of our modules. If, instead, we had chosen the Siemens route (through trichlorosilane) for producing eg-Si, the GER of a multicrystalline PV module would have been about 20% higher in the worst case (1160 kWh/m², assuming a direct process energy requirement of 215 kWh/kg eg-Si, see also 4.4) and base case.

The energy pay back time under Dutch circumstances would then increase to 4.6 yr in the worst case instead of the 3.8 yr given in table 4.4.

4.12 Conclusions

The Gross Energy Requirement of frameless m-Si modules has been estimated at 970, 400 and 180 kWh/m² cell area respectively for the worst, base and best case technology. This would result in an Energy Pay-Back Time of 3.8, 1.3 and 0.5 years respectively under Dutch irradiation conditions. Of this Gross Energy Requirement about 50% is direct process energy and 50% indirect energy use, i.e. for input materials, capital equipment, heating and lighting, etc.

Main contributors to the direct process energy are silicon purification and cell processing. Wafer thickness is the major design parameter determining the energy requirements.

In our evaluation a silicon purification process was assumed which has a relatively low energy consumption in comparison with the more common Siemens process. This may lead to a 20% underestimation of the energy requirements for a worst or base case module based on silicon from the Siemens process.

5. Summary and conclusions

5.1 Introduction

In this report we have described an environmental life-cycle assessment of multicrystalline silicon solar cell modules. The assessment was mainly focused on energy and material flows during the production of the PV modules. In order to be able to identify opportunities and possible bottlenecks in future multicrystalline silicon PV development we discerned three cases. The worst case represents an estimate of the present state of production technology. The base case is based on technologies which are most probably to be commercially available within 10 years. The best case represents an optimistic view on production technology available in 10-15 years.

In this chapter we summarize the conclusions of the energy and material flow analyses presented in the previous chapters. Based on these conclusions we give recommendations for the R&D policy in the Netherlands with regard to m-Si solar cells.

5.2 Case descriptions

In chapter 2 a schematic representation of the multicrystalline silicon solar cell studied in our report is given. We assume an improving cell efficiency from worst to best case of 13%, 16% and 18% respectively, that is to be achieved by introducing new technologies and solar cell features. In table 5.1 an overview is given of the most important differences between the cases. A more elaborate description of the discerned cases can be found in chapter 2.

The life cycle of a multicrystalline silicon PV module starts with the mining and refining of silica (quartz). Silica is reduced with carbon and the reduction step is either followed (in worst and base case) or preceded (in the best case) by a purification step. The resulting high purity silicon is melted and cast into blocks of multicrystalline silicon. The blocks are portioned into ingots, which are subsequently sliced into wafers. The wafers are processed into solar cells by etching, texturing, formation of the emitter layer, application of back surface layer and contacts and passivation and antireflective coating. The solar cells are tested, interconnected and subsequently encapsulated and framed into modules. The application of a back surface layer and the passivation step are omitted in the best case.

The general trend in the expected future developments is towards improved energy and material efficiency. This can be seen in higher process yields for high purity silicon production, casting, portioning and material production, in the usage of thinner wafers, in lowering of the metal coverage factor in contact formation, in the reduction of contouring and wafering losses and in the reduction of process energy requirements.

The most influential differences regarding energy and material requirements are the usage of thinner and larger wafers, reducing portioning and wafering losses in base and best case, and the development of a production process for solar grade silicon in the best case.

Table 5.1: The most important differences in used technologies and process parameters between the discerned cases.

process/parameter	worst case	base case	best case
silica reduction	carbothermic	carbothermic	-
high purity Si-production	UCC-process	UCC-process	reduction of high purity silica with high purity C
casting	conventional casting	impr. conventional casting	electromagnetic casting
wafer size	10 x 10 cm	12.5 x 12.5 cm	15 x 15 cm
wafer thickness	300 μ	200 μ	150 μ
wafering loss	300 μ	200 μ	150 μ
emitter back etch	no	yes	no
back surface field	yes	yes	no
back side metal coverage	100%	100%	10%
front side metal coverage	10%	7%	6%
EVA foil thickness	0.5 mm	0.5 mm	0.25 mm
module size	0.44 m ²	0.65 m ²	1 m ²
module life time	15 years	25 years	30 years
encapsulated cell efficiency	13%	16%	18%

5.3 Material analysis

Material requirements and resource depletion

If we compare the three cases to each other with regard to material requirements, we can see the influence of a decreasing wafer thickness (especially on quartz and carbon requirements), increasing wafer size (on SiC and Cu requirements) and increasing module size (on polyester and aluminum requirements).

Dominating material requirements are glass, EVA and aluminum. Other materials that are used in relatively large amounts are the input materials for mg-silicon production (i.c. quartz and carbon sources) and for wafering (mineral oil and silicon carbide). A point of attention in the best case is the large amount of HCl used in producing high purity carbon and high purity silicon. The used HCl is neutralized with Ca(OH)₂, and CaCl₂ is discharged as solid waste.

Quartz sand is a widely available material, so no problems with raw material supply are expected, even if solar cell technology is implemented on a large scale. Also with other materials no immediate problems with regard to resource depletion are expected, although the reduction of silver consumption for the contacts deserves attention.

Silver is considered as a scarce resource and 30% of the current annual silver production would be required to achieve a 5% contribution to the world electricity supply by base case

modules. A second reason for reduction of silver use arises from possible waste management problems when modules containing almost 5 g of silver per kg of waste are decommissioned. Moreover, it seems probable the reduction of silver in the contacts will also be necessary from a cost perspective before large-scale introduction of m-Si modules becomes viable.

For other, more abundant materials in the module recycling can be of interest from an energy point of view. Recycling technologies for reusing silicon from solar cells (from production waste or after module decommissioning) are not (yet) commercially available. Also for the glass and EVA recycling is difficult. The EVA foil is per definition not recyclable and the glass waste from modules may contain too much plastic to be accepted by glass recyclers. Possibly a pretreatment of the glass could suffice in removing EVA remains. The aluminum module frame seems to be the only module component which is easily recyclable.

In any case it seems necessary to reconsider the overall module design to enhance recyclability while maintaining its durability in outdoor conditions.

Process emissions

Emissions in the PV module's life cycle are at this moment largely limited to the production phase. Environmentally relevant substances which may be released in multicrystalline silicon PV module production are fluorine, chlorine, nitrate, isopropanol, SO₂, CO₂, respirable silica particles and solvents.

Fluorine and chlorine may be emitted to the air as a component of dust particles by the best case silicon purification technology. The estimated air emission is maximally 0.16 kg F and 430 kg Cl per TWh_e of electricity supplied by PV modules, which is orders of magnitude smaller than the corresponding emissions of a coal plant.

Fluorine and chlorine are also emitted to the water in all three cases (1,800 kg F and 89,000 kg Cl per TWh_e in the base case), resulting from neutralization of etching and texturing solutions and flue gases. Fluorine and chlorine contribute to the human toxicity, as does nitrate, which stems from neutralizing acids used in etching and texturing. Water-borne F- and Cl-emissions of base case PV technology are significant but still 3-5 times smaller than for a coal plant.

The non-energy-related* emissions of SO₂ (in worst and base case) are caused by using sulphur-containing carbon sources in the reduction of silica. These carbon sources are also responsible for the non-energy-related emissions of CO₂. However, the non-energy-related SO₂ and CO₂ emissions are small compared to the energy-related emissions of these gases.

Silica particles can be released in the mining and refining stage. If they are small enough to be inhaled they may cause the lung disease silicosis.

Emissions of solvents and alcohols contribute to photochemical ozone formation and both direct (the solvents itself) and indirect (ozone) respiratory problems.

Comparing the three cases to each other with regard to process emissions the influence of decreasing wafer thickness, increasing wafer size and use of a different process for producing high purity silicon is clear (especially for CO₂, SO₂ and Si powder emissions, SiC, mineral oil). Also the use of different etching, texturing and purification methods has a noticeable effect on emissions (of CaCl₂, NaCl and KCl).

* *The emissions of SO₂, NO_x and CO₂ can be distinguished into energy-related, i.e. resulting from energy use, and non-energy-related emissions, i.e. resulting from the production process itself.*

Occupational health

A number of substances are considered to pose acute and/or chronic hazards on the work force in PV industry, e.g. etchants, acids, solvents etc. Most of these materials, however, are not specific for the multicrystalline silicon PV industry. We expect the hazards of these substances to be controllable by the safety measures usually employed in chemical or semiconductor industries.

Incidental releases could result in the presence of more or less hazardous substances (e.g. silane, carbon monoxide, ammonia and silica particles) on the work floor. Safety management will have to be sufficient to take care of these risks.

5.4 Energy analysis

Energy requirement

The gross energy requirement for a multicrystalline silicon PV module (without a frame) is estimated at 400 kWh_t per m² cell area in the base case (for worst and best case this is 970 and 180 kWh_t/m² cell area respectively). It should be noted that this rather low energy requirement is partly due to our choice for the UCC process for silicon purification, which is not a commonly used method at present. Use of the Siemens process, for example, may increase the GER of a multicrystalline PV module with about 20% in the worst and base case (the best case incorporates an entirely different approach for Si purification).

Under Dutch insolation conditions the energy pay-back time of a frameless module as described in the base case is estimated at 1.3 years (3.8 resp. 0.5 yr for worst and best case)*. Addition of an aluminum frame increases the energy pay-back time with 0.4 yr in the base case.

Table 5.2: Gross energy requirement for multicrystalline silicon PV modules in kWh_t/m² cell area.

	worst case	base case	best case
Process Energy Requirement - direct	511	244	91
Process Energy Requirement - indirect	210	46	19
Gross Energy Requirement for secondary input materials (glass, EVA, etc.)	89	70	50
Gross Energy Requirement for investments	160	40	20
Total Gross Energy Requirement (excl. frame)	970	400	180
Gross Energy Requirement of frame	175	120	80

The direct process energy requirement is about half of the total required energy. The direct process energy of the cases is heavily influenced by our choice of the production route for high purity silicon. From worst to best case direct process energy for this step is expected to

* With the Siemens route the energy pay back time would have been 4.6 yr in the worst case.

decrease from 250 to 23 kWh_t per m² cell area. Another important factor is the increasing scale in cell processing, which causes direct process energy to drop from 162 kWh_t/m² in the worst case to 19 kWh_t/m² in the best case. However the decrease in both steps is also partly due to the implementation of thinner and larger wafers. Using thinner wafers results in a lower Si requirement per m², so less high purity silicon is required for producing 1 m² of PV module (cell area). Larger wafers result in less wafers per m² cell area, so less process energy will be needed for producing 1 m² of cell area.

The amount of energy required for material production is relatively low (excluding the aluminum frame), but its relative importance is increasing from worst to best case (from 9 to 28%). Using an aluminum frame adds substantially to the gross energy requirement (18%, 30% and 44% in worst, base and best case respectively). If, however, secondary aluminum is used for framing the gross energy requirement of the frame can be reduced substantially (with up to 80%). The energy requirement for material production in the best case is about halved compared to the worst case. This is mainly due to a lower carbon requirement for silica reduction and using thinner EVA foil in the best case.

The indirect energy requirement and the energy required for investments have a significant contribution to the 1 energy requirement (about 20% each). These last two contributions however have a large uncertainty and depend heavily on plant lay-out, etc.

The indirect process energy requirement and the energy requirement for investments is expected to decrease from worst to best case due to increasing batch size, a more continuous way of plant operation and lower energy requirement in equipment manufacturing.

Primary energy requirement and energy related emissions

The amount of primary energy carriers necessary for producing a certain amount of electricity with base case multicrystalline silicon PV modules is estimated to be about 20 times lower than for the present Dutch electricity supply system (see table 5.3). Also for CO₂ the base case emissions are about 20 x lower than for conventional electricity generation. The non-energy-related CO₂ emissions are about 2% of the energy-related emissions.

Table 5.3: *Energy-related emissions and primary energy requirements for electricity production with m-Si PV modules compared to the average Dutch electricity supply system in kg/GWh_e. Also the accumulated acid emission (Acidification Potential) is given in SO₂-equivalent kg's. The modules are installed in the Netherlands, insolation = 1000 kWh/m².yr).*

emission of:	PV worst case	PV base case	PV best case	average Dutch electr. supply
CO ₂ (kg/GWh _e)	167,000	31,000	9,800	666,000
SO ₂ (kg/GWh _e)	315	58	18	870
NO _x (kg/GWh _e)	370	68	21	1,210
Acidification Potential (kg/GWh _e)	574	106	33	1,720
primary energy consumption (TJ _t)	2,400	450	140	9,000

Energy-related acid emissions for the base case are 16x less with PV electricity generation than with the average Dutch electricity supply system. The non-energy-related releases of SO₂ are about 5% of the energy-related emissions for base case. Although sulphur emissions are substantially lower than for conventional electricity generation, for an energy source considered to be sustainable they are rather high, especially in the worst case.

The energy requirement and emissions per amount of electricity generated calculated in this study are in the same order of magnitude as those found for amorphous silicon modules in a previous study [5]. This is caused by a 2 times higher solar cell conversion efficiency for m-Si modules which compensates the 2 times higher energy requirement.

5.3 Policy recommendations

In view of the points of attention that were identified in the environmental assessment of multicrystalline solar cell modules, the following recommendations can be formulated:

- * The possibilities for recycling silicon wafers, both from production waste (rejected cells) and from decommissioned modules, should be investigated;
- * Possibilities for using secondary aluminum for producing module frames should be assessed;
- * Methods should be investigated to reduce the emission of fluorides in water, but also the emission of fluorides as solid waste. Alternative methods to etch the emitter without use of HF etchant should be considered;
- * The CF₄ gas which is used in the plasma etching process has a large Global Warming Potential. Therefore routine or incidental emissions of this gas should be avoided;
- * Emissions of volatile solvents and alcohols should be avoided;
- * The possibilities for reuse of silicon carbides (sawing slurry) and argon should be given attention;
- * The use of silver for contacts should be reduced to avoid problems with resource availability and problems with the management of waste from decommissioned modules.

Important options for reduction of the energy requirement of the modules are:

- the use of thinner wafers;
- the use of wafers with a larger area;
- the use of secondary aluminum for framing;
- the introduction of processes for solar grade silicon;
- monitoring and optimization of cell and module production processes with regard to energy consumption.

The first two options are largely in line with current R&D activities, so no special efforts are necessary.

Optimization of energy consumption in cell and module production may be possible by increasing batch sizes and/or plant shifts, introduction of new equipment (like IR ovens) and energy-efficient operation of equipment.

Further points of attention, which however lie outside the scope of Dutch R&D policy with regard to photovoltaic energy, are:

- * A reduction in SO₂ emissions should be achieved by using low sulphur fuels or desulphurization of flue gases, especially in the fuel-intensive processes, such as material and feedstock production and purification.

* The introduction of a process for solar grade silicon is considered as a good option for reducing the energy requirements. However, alternatives should be considered for the use of HCl for purification of the silica and carbon input materials for the solar-grade Si process considered in this study.

6. References

Note: References 56-92 were primarily used as background material for establishing the our case definitions for the multicrystalline silicon production technology.

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Appendix A:

Material requirements and releases during multicrystalline silicon solar cell module production

Table A.1: Material requirements for the production of multicrystalline silicon PV modules.

Process step/material	unit	worst case	base case	best case
Mining and refining				
- quartz	kg/kg mg-Si	2.85	2.85	2.67
Reduction of SiO₂ to Si				
- charcoal	kg/kg mg-Si	0.40	0.37	-
- Low Ash Coal	kg/kg mg-Si	0.60	0.56	-
- cokes	kg/kg mg-Si	0.40	0.37	-
- wood scrap	kg/kg mg-Si	1.40	1.32	-
Production of high purity Si				
- mg-Si	kg/kg eg-Si	1.04	1.02	-
- SilaneTetraChloride	kg/kg eg-Si	0.15	0.07	-
- silica	kg/kg sog-Si	-	-	2.67
- carbon	kg/kg sog-Si	-	-	1.10
- HCl (20%)	kg/kg sog-Si	-	-	54.60
- Na ₂ CO ₃	kg/kg sog-Si	-	-	0.90
- CaCO ₃	kg/kg sog-Si	-	-	1.70
- Al ₂ O ₃	kg/kg sog-Si	-	-	1.00
Casting/sawing/wafering				
- high purity Silicon	g/wafer	16.60	16.00	16.30
- argon gas	g/wafer	6.40	5.75	5.52
- mineral oil	g/wafer	9.90	15.50	22.30
- silicon carbide	g/wafer	12.80	20.00	28.80
- cleaning fluids	g/wafer	3.40	5.30	7.70
Etching/texturing				
- NaOH	g/wafer	5.80	-	13.10
- H ₂ SO ₄	g/wafer	4.30	-	-
- KOH	g/wafer	-	13.00	-
- HNO ₃	g/wafer	-	0.60	-
Emitter formation				
- POCl ₃	g/wafer	0.06	0.09	0.14
- HF	g/wafer	1.10	1.10	1.10
- CF ₄	g/wafer	0.07	0.08	-
Metallization				
- Ag/Al paste	g/wafer	0.50	0.78	-
- Ag paste	g/wafer	0.10	0.10	0.08
- Al paste	g/wafer	-	-	0.13

Process step/material	unit	worst case	base case	best case
Passivation				
- SiH ₄	g/wafer	0.02	0.03	0.04
- NH ₃	g/wafer	0.08	0.13	0.19
- N ₂	g/wafer	0.99	1.55	2.23
- isopropoxide	g/wafer	-	-	0.20
Module production				
- cells	cells/module	37.8	37.8	42
- tin-coated Cu strips	g/module	18	18	20
- EVA foil	g/module	434	640	490
- chem. hardened glass	g/module	3100	4700	7300
- Tedlar/Al/Tedlar	g/module	61	91	140
- Al (in Tedlar foil)	g/module	0.06	0.09	0.14
- polyester	g/module	440	440	440
- silicon adhesive	g/module	38	38	38
Framing				
- aluminum	g/module	1000	1200	1400
- polysulphide elastomer	g/module	265	390	600

Table A.2: Emissions during the production of multicrystalline silicon PV modules.

process step/materials	unit	worst case	base case	best case
Mining and refining				
- respirable dust	g/kg mg-Si	0.02	0.02	0.02
of which x-silica	g/kg mg-Si	3.40e-4	3.40e-4	3.40e-4
Reduction of SiO₂ to Si				
- CO ₂	kg/kg mg-Si	6.00	4.50	-
- SiO ₂	kg/kg mg-Si	0.01	0.01	-
- H ₂ O	kg/kg mg-Si	1.60	1.10	-
- SO ₂	kg/kg mg-Si	0.03	0.02	-
Production of high purity Si				
- Si-powder	kg/kg eg-Si	0.03	0.01	-
- SiO ₂	kg/kg eg-Si	0.05	0.03	-
- CaCl ₂	kg/kg eg-Si	0.19	0.10	15.70
- NaCl	kg/kg sog-Si	-	-	1.00
- F containing dust	g/kg sog-Si	-	-	4.00e-3
- Cl containing dust	kg/kg sog-Si	-	-	3.00e-3
- CO ₂	kg/kg sog-Si	-	-	5.30

process step/materials	unit	worst case	base case	best case
Casting/sawing/wafering				
- contaminated Si	kg/kg sog-Si	0	0	0.10
- Si (contaminated losses)	g/wafer	2.80	1.60	0.80
- argon gas	g/wafer	6.40	5.74	5.52
- mineral oil	g/wafer	9.90	15.50	22.30
- Si (in mineral oil)	g/wafer	6.90	7.20	7.80
- SiC	g/wafer	12.80	12.80	12.80
- cleaning fluids	g/wafer	3.40	3.40	3.40
Etching/texturing				
- Na ₂ SO ₄	g/wafer	3.60	-	8.10
- KCl	g/wafer	-	11.40	-
- NaNO ₃	g/wafer	-	0.80	-
Emitter formation				
- NaHPO ₃	g/wafer	0.04	0.06	0.09
- NaOCl	g/wafer	0.06	0.09	0.14
- NaF	g/wafer	0.24	0.24	0.23
- CaF ₂	g/wafer	2.10	2.10	2.00
- CO ₂	g/wafer	0.01	0.01	-
Metallization				
- evaporated solvents	g/wafer	0.14	0.21	0.05
- CO ₂ and H ₂ O	g/wafer	0.03	0.04	0.01
Passivation/ARC				
- N ₂	g/wafer	0.99	1.55	2.23
- isopropanol	g/wafer	-	-	0.16
- water (g)	g/wafer	-	-	0.02
- TiO _x (in water)	g/wafer	-	-	0.004
- TiO _x (s)	g/wafer	-	-	0.05
Module production				
- rejected cells	cells/module	1.80	1.80	2.00
- EVA cutting losses	g/module	19	29	22
- silicon adhesive	g/module	1.00	1.00	1.00
- cross linking products		p.m.	p.m.	p.m.
- rejected modules	g/module	40	62	84
Framing				
- polysulphide elastomer	g/module	21	31	48

Appendix B: Energy requirements for secondary input materials

In this appendix we discuss the assumptions concerning the energy requirements for secondary input materials (carbon, glass, copper, aluminum and plastics) which are used in for m-Si module production. Below the GER values for the present-day situation (worst case) are indicated. Base and best case values are derived from these by assuming a value for autonomous energy savings.

In the past 20 years autonomous energy savings in the industry were 1-2% per year [48]. Like Van Engelenburg [5] we have therefore assumed annual savings of 1% for the base case and 1.5% for the best case. This leads to total energy savings of about 10% (calculated over a period of 10 years) in the base case, while the best case energy savings (over a 15 year period) are about 20%.

For carbon, EVA and Tedlar this reduction does not apply to the feedstock energy, only to the process energy part of the GER.

Carbon

The Gross Energy Requirement for the different carbon sources (charcoal, etc.) and the carbon electrodes used in silica reduction is estimated by Hagedorn at 41 GJ per kg Si produced. We use this value for the worst case, while the base and best case values have been set at 40 resp. 39 GJ/kg Si produced.

Copper

According to van Heijningen et al [47] cathodic copper has a gross energy requirement of 90 GJ/ton or 25.0 kWh/kg. An additional amount of energy is required for producing copper strips out of the feedstock. For completely melting the copper feedstock 18 GJ/ton Cu is required [47]. In copper strip production complete melting of the feedstock is not necessary, the material only has to be softened. Therefore we assume an additional 10 GJ/ton copper to be required for copper strip production, resulting in 100 GJ/ton as worst case value. Base and best case values are 90 and 80 GJ/ton.

EVA

The gross energy requirement for EVA production is not known, but can be estimated roughly. The type of EVA used in PV modules is built up out of about 97% ethylene monomers and 0.3% of vinyllic acetate monomers (remaining 2.7% consists of additives). The gross energy requirement of polyethylene is about 70 MJ/kg [38]. The gross energy requirement of EVA is expected to be slightly higher, since the production of vinyllic acetate and additives requires more energy than does the production of ethylene. Furthermore foil extrusion requires an additional amount of process energy. The worst case GER value of EVA foil is therefore estimated at 75 GJ/ton [31] in the worst case. Base and best case values are 72 and 68 GJ/ton.

Tedlar

The Gross Energy Requirement for Tedlar (made up out of Poly Vinyllic Fluoride, PVF) production is roughly estimated at 115 GJ/ton [31]. The estimation is based on the assumption that PVF is produced by fluorinating vinyllic chloride, followed by purification, polymerization and foil extrusion. Base and best case values are 106 and 96 GJ/ton.

Glass

For packing glass (e.g. bottles) the gross energy requirement is about 10 GJ/ton [38]. For the production of flat and chemically hardened glass used in solar cell modules probably some additional process energy will be required. The amount of secondary glass used for PV module glass sheets will be lower than for packing glass, since it has to meet higher standards. Furthermore production of sheet glass requires more energy than the production of bottles etc and an extra amount of energy will be required for chemically hardening of the glass. This results in an estimated gross energy requirement of 15 GJ/ton [31] for the worst case. Base and best case values are 13.5 and 12 GJ/ton.

Aluminium

The gross energy requirement of aluminum feedstock is 198 GJ/ton. The gross energy required to produce anodized aluminum profiles is estimated at 230 GJ/ton [31] for the worst case. This estimation is based on the assumption that extrusion of aluminum into profiles requires an additional 20 GJ/ton and anodizing the profiles (for enhancing durability) takes another 10 GJ/ton. Base and best case values are 207 and 184 GJ/ton.

Appendix C: List of abbreviations

- ARC	:	Anti Reflective Coating
- a-Si	:	amorphous silicon
- BSF	:	Back Surface Field
- CVD	:	Chemical Vapour Deposition
- eg-Si	:	electronic grade silicon
- EPBT	:	Energy Pay-Back Time
- EPRI	:	Electrical Power Research Institute
- EVA	:	Ethyl Vinyl Acetate
- FBR	:	Fluidized Bed Reactor
- GER	:	Gross Energy Requirement
- LCA	:	Life Cycle Assessment
- m-Si	:	multicrystalline silicon
- mg-Si	:	metallurgical grade silicon
- MWS	:	Multi Wire Saw
- PECVD	:	Plasma Enhanced Chemical Vapour Deposition
- PER	:	Process Energy Requirement
- PV	:	PhotoVoltaics
- sg-Si	:	semiconductor grade silicon
- sog-Si	:	solar grade silicon
- STC	:	Silane Tetra Chloride
- TCS	:	Tri Chloro Silane
- UCC	:	Union Carbide Corporation