Environmental Aspects of Solar Cell Modules

Summary Report

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Report nr. 96074
ISBN 90-73958-17-2

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A study in commission by the
Netherlands Agency for Energy and the Environment (NOVEM)

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Abstract

In this report we summarize and update the results of a study project on the environmental aspects of photovoltaic solar cell technology. Four major types of solar cell modules, based on respectively multicrystalline silicon, amorphous silicon, cadmium telluride and copper indium selenide are reviewed with special attention to future expected technology developments.

For each module type an assessment is made of the potential environmental impacts in case of large scale implementation of the technology. In principle the entire module life cycle is taken into consideration: from resource mining, via module production and module utilization until module decommissioning and waste handling.

In the report for each module type the following aspects are discussed: energy requirements and energy pay-back time, material requirements and resource depletion, environmental emissions, waste handling, possibilities for recycling of modules, occupational health and safety and external safety.

Acknowledgements:

The author would like to thank the Netherlands Agency for Energy and the Environment, Novem, for their comissioning of this study. Also I want to thank dr. R. Schropp, prof. dr. W. Sinke, prof. dr. J. Nijs and dr. ir. R. van Zolingen for sharing with us their knowledge on solar cell production technology.

Finally I want to mention the import contribution of my co-workers Barend van Engelenburg and Dian Phylipsen who where the leading authors of two of the three reports which form the basis of this summary and update document.

Contents:

1 Introduction

It is widely recognized that photovoltaic solar energy conversion has the potential to become a major energy source in the next century. Although photovoltaic solar energy (PV) is clearly a renewable energy source, the question whether it is also a "sustainable technology" needs more careful consideration. The potential environmental risks and the energy requirements of (the components of) a PV system should be investigated over its entire life-cycle in order to answer this question.

If such analyses are made before large-scale implementation of the technology has started, potential bottlenecks can be identified so that R&D priorities can be set accordingly to reduce or eliminate the bottlenecks beforehand. 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 series of studies on potential environmental and safety risks for a number of solar cell technologies. The objective of the studies is to identify potential bottlenecks for each technology and to formulate ensuing recommendations with regard to the photovoltaic R&D policy in the Netherlands. In the study the potential environmental effects of PV modules are investigated for their entire life-cycle, that is from raw material mining through module production and utilization to module decommissioning and, possibly, recycling.

It was agreed with Novem that four different types of solar cells would be investigated in these studies, namely:

1) **Multicrystalline silicon** cells (mc-Si; also called semi- or polycrystalline silicon);
2) **Amorphous silicon** cells (a-Si);
3) **Cadmium telluride** cells (CdTe);
4) **Copper indium selenide** cells ($CuInSe_2$; also shortened to CIS);

The studies concerning the above-mentioned cell technologies were reported in three[*] separate documents [1-3]. In this report we will present a summary of the method of approach and the obtained results for all four cell types. It should be noted, however, that the methodology and the scope of the analyses has developed in the course of the project. Because in this summary report we wanted to present results of the four cell types on a more or less comparable basis, some figures presented here can differ somewhat from previously published figures. These differences will be pointed out and explained at the place where they occur. Also in several places information is given from recent studies which update or supplement the original studies.

Other authors have previously published studies in the field of environmental, health and safety aspects of PV technology. A landmark study was published by Neff in 1981 [4], but recent progress in photovoltaic technology has reduced its relevance. Since 1980 Moskowitz and coworkers have published a number of very useful reports [5-10] but their main focus was on (occupational) health and safety risks and less on environmental risks. Based on these studies Alsema and Turkenburg gave a review of environmental aspects of PV technology in the context of the Dutch energy supply [11].

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[*] Because CdTe and CIS technologies have many similarities they were reported on in a single volume. In the following chapters we will mostly treat them under one subject heading, too.

More recent work by Moskowitz et al. adresses issues like gas hazard management, cadmium use and module decomissioning [12-15].

A very thorough study of energy and material flows in silicon solar cell technology (crystalline and amorphous) was performed by Hagedorn et al. [16-19, see also 20]. The limitation of this work, however, is that it focuses on module production technology as it existed around 1990, and gave only limited consideration to the effects of future technological developments. Nonetheless, the Hagedorn study was our major source for detailed data on the energy requirements and material flows of present-day production processes for crystalline and amorphous silicon modules.

Finally we want to mention the work of Steinberger and coworkers who recently finished an extensive study of the environmental and health aspects of CdTe and CIS modules [21]. However, their results became available only at a late stage during the preparation of this report. For this reason the new information from their work has only been incorporated on one critical point (fire-related emissions).

In our own studies which form the basis for this summary report we have tried to integrate results from previous studies in the framework of the Life Cycle Assessment (LCA) methodology and to extend the scope towards future technologies which seem probable for large-scale module production.

In order to understand the sensitivity of the results with respect to possible future developments, we will draw up three different sets of assumptions concerning the future status of the technology for each cell type. These sets of assumptions will be called *worst, base and best case* technology. In this report the base case represents the most probable technological status at the time of large-scale deployment. The worst case reflects the status of present-day commercial production technology. Finally, the best case represents an more optimistic view on future technology.

As already indicated, this report will be limited to a life-cycle assessment of solar cell *modules.* In another report the results are described of a LCA of a complete PV system, i.c. a roof-integrated system, which incorporates amorphous silicon modules, a support structure and a power conditioner [22].

In this report we will first introduce briefly the method of environmental Life Cycle Assessment and further define the goal and scope of our assessment study. Subsequently, we will discuss the most important assumptions concerning module and cell characteristics, production methods, etc. Next, some results are presented, among which the expected emissions to the environment and the energy requirements. Finally we will draw some conclusions concerning potential environmental bottlenecks of PV modules.

2 Life Cycle Assessment: Goal, Method and Scope

2.1 LCA goal

In this study we want to investigate the environmental bottle-necks which might arise when PV modules are deployed on a large scale for the mondial energy supply.
A consequence of this objective is that mondial production levels of the order of GWp's per year should be considered rather the current MWp production level. As a reference one can keep in mind that a yearly solar cell production of more than 10 GWp/yr will be required to sustain a PV capacity that can contribute 5% to current mondial electricity supply (1 TWy/yr).

2.2 LCA Method

In the project we made use of the method of environmental Life Cycle Assessment (LCA), a methodological framework for the analysis of environmental aspects of product life-cycles, which has evolved over the past few years. In such a LCA the material and energy 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 product life cycle is divided into a number of processes, each of which is described by the typical product input and output flow, secondary material inputs, energy input, process yield, water and air emissions, solid waste production and the output of reusable (secondary) materials. By chaining a number of relevant processes into a product life cycle and accounting all material flows through these processes it becomes possible to assess the total impact on the environment and on energy and raw material resources for the entire product life cycle.

One consequence of our study objective is that we will have to make projections about the technological status of future production processes. Because this necessarily involves major uncertainties we will distinguish three cases: the worst case reflecting the status of present-day commercial production technology, the base case representing the most probable technological status at the time of large-scale deployment, and finally the best case representing an optimistic view on technology development. For the base case technology we assume implementation within the next 10 years, while the time frame for the (possible) realization of best case technology is 15 years.

Regarding our assessment method it should further be noted that in a full Life Cycle Assessment a certain procedure is followed involving a number of steps, such as: definition of LCA goal and scope, drawing up of the inventory table of environmental interventions and classification and evaluation of these interventions [23, 24]. For the purpose of this study where we consider future production technologies not all of the prescribed LCA steps are relevant or practicable, because of lack of data etc. For these reasons our studies cannot claim to be “full” LCA studies, in which the majority of the material flows is inventarised and the environmental impacts are evaluated.

For example in our first study on CdTe and CIS modules [1], we restricted the material flow analysis to the elements Cd, Te, Se, and In and did not consider any auxilary material usage. The main reason for this was the lack of detailed information on (future) production processes for these module types. Also at that time the methodological framework for Life Cycle Assessments had not yet been fully developed so that the terminology and reporting format in our study deviates from the standards which later evolved for LCA studies in the Netherlands.
In the amorphous silicon study [2] and the mulitcrystalline silicon study [3] we had access to more detailed data on production technology which allowed us to the take into account most material flows. Also we adhered more closely to the “standards” regarding LCA terminology

and study set-up. Still, we decided not to perform an analysis of environmental impacts after our inventarisation of material flows, because: 1) there are insufficient data to allow an reliable impact evaluation for all emitted substances and 2) emission estimates for the future technology cases (base and best case) are often to uncertain to make reliable impact evaluations for these cases.

2.3 LCA scope and the functional unit

The scope of our material flow analysis is restricted to *direct* material inputs only, which means that the production of for example glass or aluminium is outside our *system boundary* and is not considered in our analysis.

The scope for the analysis of energy requirements, however, is broader and includes also the the energy use for the production of glass and aluminium and for the production of capital equipment. In the energy analysis auxilary materials which are used in relatively small quantities (e.g. solvents, etchants, hydrogen, argon) were not taken into account, mainly because energy data are unavailable for most of these products. Figures 2.1 and 2.2 illustrate the definition of the system boundaries for the materials and energy analyses for the example of mc-Si technology.

The scope definition given above implies that the non-energy related emissions from the production of aluminium and glass are not accounted for in this study[*]. Such aspects, however, should be investigated in relation to module mounting technology (see for example [22, 25]).

The functional unit for our Life-Cycle Assessment, that is the unit of end-product to be considered, we have defined as 1 square meter of *cell* area, manufactured in a commercial scale production process. If needed, corresponding values per m^2 module area can be derived by applying the cell/module area ratio.

The photovoltaic efficiency will refer to the total area stabilized energy conversion efficiency of the *cell* as it is encapsulated in the module[**] (encapsulated cell efficiency).

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[*] This may lead to an underestimation of environmental impacts in the impact classes of global warming, acidification, and human toxicity, mainly as a result of the emissions from aluminium production. However, the aluminium requirements for a PV module frame are strongly dependent on module dimensions and mounting method. Therefore, these effects should be studied in the broader context of PV *system* environmental impacts. Further note that glass and Al requirements are independent of cell type, so that cell type comparisons are not affected by this limitation of the study scope.

[**] The main reason for this choice is that module efficiency is a less clearly defined parameter, and that its value is depedent on cell/module area ratio (packing factor). Cell efficiency values give a better indication of technology status and can easily be translated into energy output values.

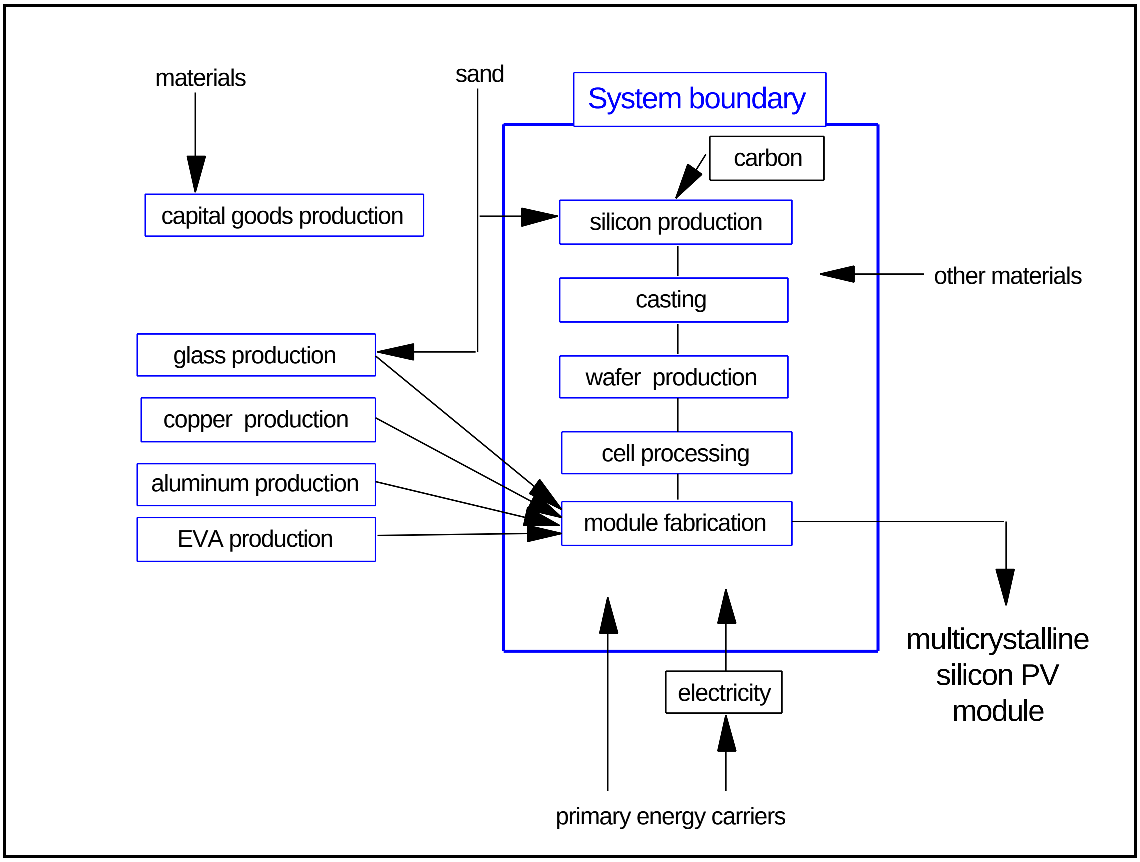

Figure 2.1: System boundary for *material flow* analysis in the case of mc-Si technology.

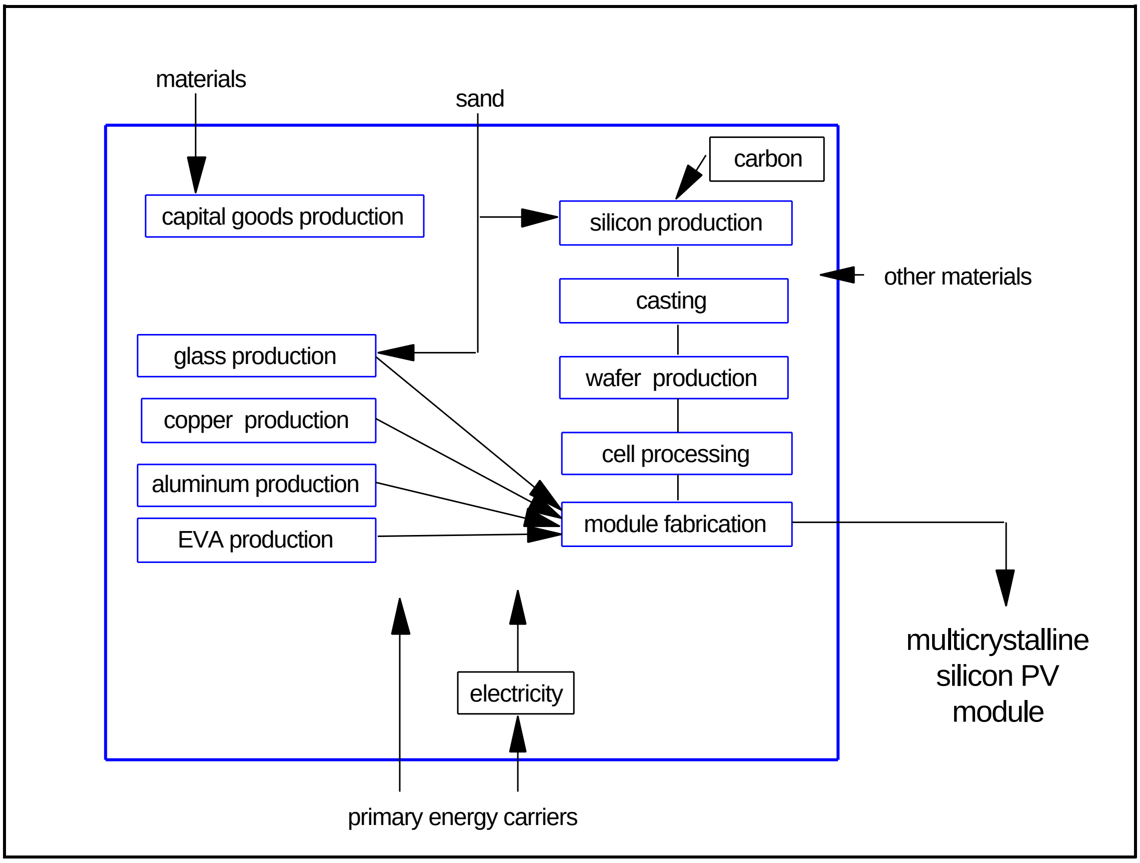

Figure 2.2: System boundary for the *energy analysis* in the case of mc-Si technology

3 Major assumptions

3.1 Multicrystalline silicon modules

Cell, module and process characteristics

Multicrystalline silicon (mc-Si) technology is one of the major technologies for production of solar cell modules and this type of modules presently has a share of some 25% of the PV module market. Present-day mc-Si modules are generally composed of 36-40 interconnected solar cells, where each solar cell consists of a silicon wafer with a surface area of about 10x10 cm^2 and a thickness of 0,2-0,3 mm.

Multicrystalline silicon solar cell technology is closely connected to the older *mono*crystalline solar cell technology (which is still the most important technology with a 60% market share). The main difference between multi- and monocrystalline silicon solar cell manufacturing is found in the crystallization process, while less important differences may be encountered in the solar cell processing itself (e.g. passivation). To a large extent, however, the material flows and emissions found in multicrystalline silicon technology will also be found in monocrystalline silicon technology. Therefore the results of our study on multicrystalline silicon[*] will probably also give an fair indication of the environmental aspects of monocrystalline silicon technology [cf. 18].

In our study we assume the encapsulated cell efficiency for mc-Si to improve from worst to base and best case from 13% to 16% and 18% respectively, a development which is to be achieved by introducing new technologies and solar cell features. In tables 3.1 and 3.2 an overview is given of the most important differences between the cases.

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. For the worst and base case we depart from the process developed by Union Carbide Corp. in which SiCl4 is hydrogenated and subsequently distilled to semiconductor grade (sg) silane. This silane can then be converted to solid polycrystalline silicon, or it can be used as source gas for amorphous silicon solar cell production (see next section).

Subsequently the high purity polycrystalline silicon is melted and cast into large blocks of multi- (or semi-)crystalline 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, passivation and deposition of the antireflective coating. Finally 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 and 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.

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[*] The reason we investigate multicrystalline silicon technology instead of monocrystalline, is that multicrystalline Si production technology is a major subject of research within the Dutch Photovoltaic R&D Program whereas monocrystalline technology is not.

Table 3.1: Cell and module characteristics for multicrystalline silicon technology

	worst case	base case	best case
cell efficiency[1] (%)	13	16	18
wafer size (cm^2)	10 x 10	12.5 x 12.5	15 x 15
wafer thickness (µm)	300	200	150
cells/module	36	36	40
module size (m^2)	0.44	0.65	1.00
cell/module area ratio	0.82	0.87	0.90
module efficiency[2] (%)	10.6	13.8	16.2
module structure:			
- glass (mm)	3	3	3
- EVA[3] (mm)	2 x 0.5	2 x 0.5	2 x 0.25
- Tedlar/Al/Tedlar (µm)	125	125	125
module life time (yr)	15	25	30

Notes: 1) Efficiency is for the cell *as encapsulated and interconnected in the module*.
2) derived values;
3) EVA = Ethyl Vinyl Acetate;

Table 3.2: Major process characteristics for mc-Si module production.

	worst case	base case	best case
sg-Si production	UCC[1]-process	UCC[1]-process	reduction of hp-SiO_2
casting	conventional	advanced conventional	electro-magnetic
wafering loss (µm)	300	200	150
back metal coverage (%)	100	100	10
front metal coverage (%)	10	7	6
solar cell process yield[2]	95%	95%	95%

Notes: 1) process developed by Union Carbide Corporation to produce solar grade silane/silicon;
2) for cell processing only, not for Si production and wafering.

Module Use
Negligible material inputs and/or emissions are expected during the utilization phase of the module (only from occasional washing). Significant emissions due to fires are not expected from mc-Si modules.
In this phase the module will produce electrical energy, the amount of which depends on module efficiency and location. Module lifetimes of resp. 15, 25 and 30 years were assumed for the three cases.

Module decommissioning
At the end of the module lifetime the PV system will be decommissioned and the resulting waste will have to be disposed in a responsible way. Options for recycling of the silicon wafer have been investigated but are at this moment not commercially available. Because there is hardly any data available on the technology of mc-Si module recycling we did not consider this in our study.

3.2 Amorphous silicon modules

Cell, module and process characteristics
Amorphous silicon (a-Si) solar cell technology is very different from crystalline silicon cell technology, in that the amorphous silicon cell consist of a very thin layer of amorphous (i.e. non-crystalline) material. The low requirement of cell material and the possibility of large-area cell manufacturing processes, makes a-Si technology a potential candidate for production of low-cost modules. Furthermore with a-Si there is the possibility of cell stacking, an approach in which two or three different a-Si solar cells are stacked into a tandem or triple structure. and which may ultimately lead to a higher conversion efficiency. Mainly because of their relatively low efficiency a-Si modules have only a modest market share of about 14% at present.

Our worst case and base case definitions for the amorphous silicon technology are both based on a tandem cell structure, be it with differing i-layer thicknesses (see table 3.3). For the best case we assume a triple-junction structure based on a-SiC/a-Si/a-SiGe. The a-Si layers are deposited on a glass substrate by way of the Plasma Enhanced Chemical Vapour Deposition with a material utilization rate which increases from 15 to 70% (table 3.4).
In all three cases the front-side contact layer consists of tinoxyde doped with fluorine and deposited by CVD, while the back-contact consists of a sputtered or evaporated aliminium layer.
The silane source gas for a-Si deposition is produced by the same process from Union Carbide Corp. which was assumed for the mc-Si technology.
Module encapsulation is changed from two glass sheets for the worst and base case (2 x3 mm resp. 2 x 2 mm), to one 2 mm glass sheet with a sprayed-on back-side foil in the best case.

Module use
Considerations for the module utilization phase are similar as for mc-Si.

Module decommissioning
After decommissioning the a-Si module can be disposed as solid waste without problems as all module components (including metals) are inert or relatively harmless.

Recycling of the glass or reuse of the glass sheet plus SnO_2-layer is possible in principle. However, to maintain comparability with other considered module types we have not considered the effects of these recycling options.

Table 3.3: Cell and module characteristics for a-Si technology.

	worst case	base case	best case
Cell structure	a-SiC/a-Si (tandem)	a-SiC/a-Si (tandem)	a-SiC/a-Si/a-SiGe (triple)
Cell efficiency[1] (%)	6	10	15
SnO_2 contact thickness (nm)	1000	600	500
p-layer thickness[2] (nm)	15	20	20
i-layer thickness[2] (nm)	500	300	300
n-layer thickness[2] (nm)	35	35	35
Al back contact (nm)	1000	1000	1000
Module size (m^2)	1	1	1
Cell/module area ratio	0.94	0.94	0.94
Module efficiency[3] (%)	5.6	9.4	14.1
module structure:			
- front glass (mm)	3	2	3
- EVA (mm)	0.5	0.5	0.5
- back glass (mm)	3	2	-
- back foil (mm)	-	-	<0.1[4]
Module life time (yr)	15	25	30

Notes:
1) Stabilized cell efficiency;
2) Layer thickness of the p, i and n- layers refers to total thickness in the tandem or triple structure.
3) Derived values;
4) back foil material use was neglected;

Table 3.4: Major process characteristics for a-Si module production

	worst case	base case	best case
silane production	UCC[1]-process	UCC[1]-process	UCC[1]-process
silane utilization	0.15	0.40	0.70
SnO_2 utilization	0.25	0.40	0.85
Al utilization	0.30	0.50	0.70
solar cell process yield[2]	0.90	0.94	0.98

Notes: 1) process developed by Union Carbide Corporation to produce solar grade silane/silicon;
2) for cell/module processing only, not for silane production;

3.3 CdTe and CIS modules

Cell, module and process characteristics

Cadmium telluride (CdTe) and copper indium selenide ($CuInSe_2$; also: CIS) solar cells are two other representatives of thin-film solar cell technology, which is characterized by the use very thin layers of cell material (<50 µm). For CdTe and CIS modules also good prospects exist for low-cost production processes and for efficiency enhancement by way of cell stacking.

Production technology for CdTe and CIS solar cells is much less established than for mc-Si and a-Si. CdTe modules are produced only on a small scale (Matshushita, BP Solar), while CIS cells have up to now not been produced on commercial basis.

Specific data about production technology are therefore scarce. For this reason we have limited our investigation of CdTe and CIS technology to assessment of the material flows for Cd, Te, In, and Se[*] and to an analysis of the energy requirements.

Table 3.5, 3.6 and 3.7 summarize the main cell and module characteristics that we have assumed for CdTe respectively CIS modules.

Note that, in deviation of the assumption for a-Si modules, and in deviation of our original study, we have maintained the back glass cover for the best case CdTe/CIS module. Reason for this is that lower emissions of heavy metals, especially in fires and in waste dump sites are expected from modules with a back glass cover.

Table 3.5: Cell characteristics for CdTe technology.

	worst case	base case	best case
CdS layer (µm)	0.2	0.15	0.1
CdTe layer (µm)	4	2	1
cell efficiency (%)	10[1]	15	18

Note: 1) CdTe modules presently on the market have a somewhat lower efficiency; however a 10% cell efficiency seems achievable within a few years.

Table 3.6: Cell characteristics for CIS technology.

	worst case	base case	best case
CdS layer (µm)	0.1	0.05	0.02
$CuInSe_2$ layer (µm)	4	2	1
cell efficiency (%)	10[1]	15	18

Note: 1) Although prototype modules with 10% efficiency have been demonstrated, no CIS modules are commercially available yet.

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[*] Presently Ga is often added as a fourth constituent of CIS (then CIGS) solar cells. We have not considered any gallium use in our study, however.

Table 3.7: Module characteristics for CdTe and CIS technology.

	worst case	base case	best case
module structure: - front glass (mm) - EVA (mm) - back glass (mm)	 3 0.5 3	 2 0.5 2	 2 0.5 2[1]
Module size (m^2)	1	1	1
Cell/module area ratio	0.94	0.94	0.94
Module efficiency[2] (%)	9.4	14.1	16.9
module life time (yr)	15[3]	25[3]	30

Notes: 1) Differs from original study (see text);
2) Derived values;
3) Differs from original study; here worst and base case lifetimes are set equal to values for a-Si and mc-Si in order to facilitate comparison.

Regarding the production technology we assume for deposition of the CdS and CdTe layers in the CdTe cell that the electrodeposition process will be employed, with material utilization factors of 90 to 99% (table 3.8). For the CIS cell first the CdS layer is sputtered, while the CIS layer is prepared by physical vapour deposition of copper and indium followed by selenization (reaction with H_2Se gas).

Table 3.8: Major production process characteristics for CdTe and CIS technology.

		worst case	base case	best case
CdTe cell	material utilization (Cd, Te)	0.90	0.95	0.99
CIS cell	material utilization (Cd, In, Se)	0.60	0.70	0.80
process yield[1]		0.60	0.70	0.80
Cd emission to air (mg/kg)[2]		500	100	50
Se, Te, In emission to air (mg/kg)[2]		5000	1000	500

Notes: 1) cell/module production only;
2) emission in mg per kg throughput.

The environmental impacts from the mining of Cd, In, Se and Te, materials which are all produced as a by-product of zinc or copper mining, have been calculated as a fraction the total impact of the mining process. Based on the economic value of by-product and main product these fractions were set at respectively 2.5%, 0.2%, 0.2% and 0.36%.

The base case emission rates for Cd were based on emission data of a cadmium production facility in The Netherlands. Because emission control for Se, Te and In will probably be less strict we have assumed emission rates for these substances to be a factor 10 higher.

Note that emissions to water have been considered but will not be presented in this summary.

Module use

During use of the modules there is a risk that they will be involved in a fire. This is especially the case for modules installed on the roof of a building. Emission of a certain fraction of cell material in CdTe and CIS cells may then occur. Although acute health risks from these emissions are improbable, the overall environmental impacts still need consideration. Therefore an estimate of the fire risk and worst to best case assumptions for the emitted fraction have been made (table 3.9). On this point recent information from the study by Steinberger et al. [21] was used to update the assumptions on emitted cell material.

Different other routes for human exposure to Cd, Te or Se during the use of CdTe and CIS modules have also been investigated by Steinberger et al, but in all cases the risks were found to be small.

Table 3.9: Assumptions on emissions from module use and decommissioning for CdTe and CIS technology.

	worst case	base case	best case
fraction of cell material released during fire[1]:			
- Cd, Te	0.10	0.75	0.05
- Se	1.00	0.75	0.50
fire risk[2] (yr^{-})	10^{-4}	10^{-4}	10^{-4}
fraction of decomm. modules entering waste incineration	0.10	0.02	0
fraction of heavy metals emitted to air from waste incineration[3]	0.0015	0.0015	0.0015
fraction of decomm. modules going to household dump site[4]	0	0.03	0.01
fraction of heavy metals emitted to water from waste dump	0.001	0.001	0.001

Notes:
1) Worst case emission rates are based on recent experimental data (see [21]); base and worst case emissions were set at 75% resp 50% of worst case emission. The reductions for the base and best case might be achieved by enhanced module encapsulation. Note that in the original report emission rates were assumed to be much higher for Cd and Te. All results presented below are based on the new assumptions.
2) Estimated risk for roof-top installations, risk will be lower for ground-based systems.
3) In the original report on CdTe/CIS this fraction was estimated much higher, at 0.10. However, recent studies indicate that Cd emissions from waste incinerators lie in the range of 0.1-0.15% [26]. All results presented below are based on the new assumption.
4) Total fraction of decommissioned modules treated as waste (incineration plus dumping) is assumed to be resp. 0.10, 0.05 and 0.01 for worst, base and best case; of this amount a fraction of 1.0, 0.6 resp. 0 is incinerated.

Module decommissioning

In view of the heavy metal content of CdTe and CIS modules separate collection of decommissioned modules seems advisable. However, it is probable that a small fraction of the modules will still end up in household waste which may either be incinerated or disposed of at a landfill site. In each case a certain emission of the heavy metals to the environment will result. Relevant assumptions to estimate these emissions are given in table 3.7.

Although recycling of CdTe and CIS modules is subject of investigations, there is not sufficient data to consider the effects of a possible recycling process at this time.

4 Energy analysis

4.1 Introduction

In this chapter we will analyse the Gross Energy Requirement (GER) of the considered solar cell modules. A GER value gives the total amount of primary energy incorporated in a product, as a result of all the production processes necessary to manufacture it, including the heating value of the product (if relevant). The energy required in a specific process step is called the Process Energy Requirement (PER). This PER can be separated into a direct and an indirect part where the first value gives the electrical and fuel energy which is consumed in the production process itself, while the indirect PER represents the "overhead" amount of energy consumption due to for example lighting, heating and ventilation. So cumulation of all PER values for the subsequent steps in a production process and summation with the product's heating value results in the GER value of the product.

In our analysis of module GER values we will distinguish the following contributions: the Gross Energy Requirement of the input materials (GER input), the Process Energy Requirements (PER) and the Gross Energy Requirement of the capital goods (GER capital). Energy required for the production of the input materials like glass or EVA is also taken into account. In the base and best cases a 10% resp 20% autonomous reduction on the Process Energy Requirements is assumed for commodities like glass, EVA and aluminium.

Although energy requirements will generally be a mix of thermal (fuel) and an electrical energy all results will be presented here in thermal energy units. For the conversion of thermal energy units (kWh_{th}) to electrical energy units (kWh_e) a factor of resp. 0.39, 0.42 and 0.45 was used, reflecting the expected improvements in average conversion efficiency of the (Dutch) electricity supply.

The Energy Pay-Back Time (EPBT) for the different cases will also be presented. This EPBT will be calculated for a PV system under Dutch irradiation conditions (1000 $kWh/m^2/yr$) and "global average" irradiation (1700 $kWh/m^2/yr$). Furthermore we assumed a yearly Performance Ratio (a measure of system performance) of respectively 0.75, 0.80 and 0.85 for the worst, base and best case. Appendix A gives an overview of energy production data per m^2 module area in the different cases.

Note that energy pay-back times are given for frameless modules only because Balance-of-system components like support structures etc. were not evaluated in our studies and because framing requirements are dependent on the method of installation of the modules. Some remarks on energy requirements of module frames and support structures will be given in section 4.5

4.2 Multicrystalline silicon modules

In table 4.1 we show in which way the energy requirements of the mc-Si module are built up starting with purification, resulting in solar grade silicon with a Gross Energy Requirement of 167 kWh_{th}/kg (worst case). Then the silicon is casted and sawed into wafers, which have a threefold increased GER value, mainly due to material losses. The worst case wafer GER value of 509 kWh_{th} per kg material, which is equivalent to 350 kWh_{th} per m^2 cell area, then forms one of the energy inputs for the solar cell and module manufacturing process.

Other energy inputs in this process are the Gross Energy Requirements of secondary (i.e. non-wafer) input materials, the Process Energy Requirements and the GER capital. The last four energy requirement figures can then be added up to obtain the final GER value of 969 kWh_{th} per m^2 cell area for the finished module.

Table 4.1: Energy requirements for multicrystalline silicon solar cell modules. (See section 4.1 for an explanation of the terms GER and PER).

Process	Energy requirement	unit[1]	worst case	base case	best case
Si reduction & purification	GER sg-silicon	kWh$_{th}$/kg	167	153	45
casting and wafering	GER wafer	kWh$_{th}$/kg	509	450	210
cell & module processing	GER wafer	kWh$_{th}$/m^2	350	207	72
	GER other input materials (glass, EVA, etc.)	kWh$_{th}$/m^2	68	59	42
	PER (direct + indirect)[2]	kWh$_{th}$/m^2	395	94	47
	GER capital goods[2]	kWh$_{th}$/m^2	156	39	19
Finished module	GER module (excl. frame)	kWh$_{th}$/m^2	969	399	180
	Energy Pay-Back Time (Netherlands)	yr	3.8	1.3	0.5
	Energy Pay-Back Time (global average)	yr	2.3	0.8	0.3

Notes: 1) m^2 refers to total cell area
2) Values refer to cell and module processing only, therefore apparently different from values in original study.

Going from worst to best case we can see that the movement towards thinner wafers and the introduction of new Si purification process may bring down the GER of the wafer with a factor of five. In the cell processing itself increased batch sizes, increased utilization of equipment and modernization of processes have a large effect on the contributions from direct and indirect PER and from GER capital. Much less reduction is seen in the energy requirement for secondary materials. All in all it is clear there are good prospects for reduction of energy requirements, and that this can happen largely by way of technology improvements which are likely to be introduced for reasons of cost reduction or cell performance enhancement.

It should be noted that the choice for the UCC-process for silicon purification in our evaluations gives an slightly optimistic image of the energy requirement of mc-Si modules. If the more common Siemens purification process was assumed energy requirements and energy pay back times for the worst and base would be approximately 20% higher. (Best case results are not influenced by this choice because an entirely different process is assumed there).

Other estimates for the Gross Energy Requirement of mc-Si modules have been made by Palz and Zibetta and by Hagedorn. Palz and Zibetta [27] estimated the GER for mc-Si modules based on 190 µm wafers at about 260 kWh$_{th}$/m^2. Their value 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, like they say, the energy remaining for the module itself might be estimated at some 140-180 kWh_{th}/m^2. This value seems very low in comparison with our base and best case estimates (400 resp. 180 kWh_{th}/m^2). In our view the Palz and Zibetta estimate is too optimistic and certainly not representative for present-day technology.

If we compare Hagedorn's estimate of the GER for "present-day" (i.c. 1988) mc-Si technology [16, 17] with our worst case. results we find that Hagedorn's value is twice as high as ours. This can be explained by our assumption of thinner wafers (300 µm vs 450 µm), 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 the energy requirements of input materials and cell production processes. Although our results may be slightly optimistic (see above) we think that they give a fair indication of the energy requirements of present-day and future mc-Si technology.

Calculation of the energy pay-back time for our three cases shows that for the worst case module the pay-back time is rather high, almost 4 years under Dutch conditions, but the base and best case estimates give an acceptable to good pay-back time of 1.3 to 0.5 years. Under globally averaged irradiation conditions the EPBT is in all cases less than 2.5 years.

4.3 Amorphous silicon modules

In the amorphous silicon module also purified silicon (in the form of silane) is used as feedstock for preparation of the solar cell. However, because the a-Si cell itself is almost a factor thousand thinner than the mc-Si cell the contribution to the energy requirements from the silane is practically negligible (1.6-0.2 kWh_{th} per m^2 cell area).

Table 4.2: Energy requirements for amorphous silicon solar cell modules. (See section 4.1 for an explanation of the terms GER and PER).

Process	Energy requirement	unit[1]	worst case	base case	best case
Si reduction & purification	GER silane[2]	kWh_{th}/kg	167	153	153
Cell & module processing	GER silane input	kWh_{th}/m^2	1.6	0.3	0.2
	GER other input materials[3] (glass, EVA)	kWh_{th}/m^2	82	53	37
	PER[4] (direct + indirect)	kWh_{th}/m^2	320	108	73
	GER capital[4]	kWh_{th}/m^2	123	63	38
Finished module	GER module (excl. frame)	kWh_{th}/m^2	525	224	149
	Energy Pay-Back Time[5] (Netherlands)	yr	4.6	1.2	0.6
	Energy Pay-Back Time[5] (global average)	yr	2.7	0.7	0.4

Notes: 1) m^2 refers to total **cell** area;
2) Updated GER value for silane (equal to GER for sg-silicium from UCC-process, cf. section 5.2);
3) Updated GER values for glass (4.2 kWh_{th}/kg) and EVA (20.8 kWh_{th}/kg) used and accounting for cell/module area ratio of 0.94; therefore different from original study;
4) For cell and module processing only;
5) Previously published EPBT values neglected PV system losses (PR=1).

We see that for a-Si technology too, there is a significant potential for reduction of energy requirements, leading to energy requirements of less than 200 kWh_{th}/m2 for frameless modules. For the present-day technology, however, the energy requirements are still relatively high, with the process steps for a-Si and back contact deposition as important contributors.

Our analyses further show that the glass makes up about 80% of the Gross Energy Requirements for the input materials. Replacing the glass by synthetic materials does not offer much prospects for energy reduction as most plastics have a higher energy requirement than glass[*]. Only the use of thin foils as substrate and cover material may lead to reductions in energy requirements, but then the module would loose its rigidity, requiring novel mounting concepts. Another option could be the recycling of the module glass at the end of its lifetime, but this will not result a significant reduction of the energy requirement either (approx. 7 kWh_{th}/m^2).

Finally one can see that the capital goods contribute significantly to the total energy requirements of the module. Note, however, that these estimates are based on economic-statistical data on energy use per dollar invested for certain product categories and therefore have a rather high degree of uncertainty. Still, the high contribution of capital goods is typical

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[*] For example, use of an encapsulation based on a 2 mm polypropylene (PP) substrate and 0.13 mm ethylene tetrafluoro ethylene co-polymer (ETFE) will require approximately 34 kWh_{th}/m^2 [25], while a double glass encapsulation requires 40 kWh_{th}/m^2. So the reduction in energy requirement is only modest.

for a "high-tech" product as PV modules and quite different from the situation for more conventional industrial products.

Because of the relatively low efficiency of a-Si modules the energy pay-back time is in the worst case higher than for a mc-Si module. For base and best case a-Si module pay-back times are comparable with mc-Si base and best case values.
This remarkable result indicates that energy requirements for processing, glass, EVA, capital goods and non-process appliances (heating, lighting, emission control) are so high that for a module with a relatively low efficiency an unfavourable energy pay-back time may be found. Evidently the greatly reduced requirement of cell material in the a-Si module does not compensate for the lower efficiency, at least in energy terms.

The study by Palz and Zibetta [27] on the energy requirements for a 1990 production process of a-Si modules arrives at a GER value of about 170 kWh_{th}/m^2, which is much lower than our worst case estimate. Hagedorn [16], on the other hand, gives at about the same value (500 kWh_{th}/m^2) for present-day technology as we do. Lacking detail in the Palz and Zibetta paper makes it difficult to analyze the reason for these differences.
In comparison with the estimates below for CdTe and CIS modules the Process Energy Requirement for the worst case a-Si module seems somewhat high. It might be that the Hagedorn study which formed the basis for our worst case estimate is somewhat conservative on this point and that more modern production facilities will have a lower proces energy requirement.

4.4 CdTe and CIS modules

The energy requirements for production of CdTe and CIS modules are given in table 4.3.
Here estimates for the direct Process Energy Requirement from our CdTe/CIS study are combined with new estimates for the indirect PER (derived from the a-Si study) and for the GER of glass and EVA. The GER for the input of Cd and Te resp Cu, In and Se are neglected but this will give only a small error (cf. GER silane input in table 5.2).
In our view these new results provide a better estimate for the total energy requirement of CdTe and CIS than the previously published values. Still the uncertainty in the values is larger than for a-Si and mc-Si technology because relevant data from a production environment are not available for CdTe/CIS technology.
From the table we can see the Gross Energy Requirements for the CdTe module are somewhat lower than for the a-Si module, while the CIS estimates are significantly higher than those for CdTe. The latter is entirely due to the evaporation/selenization process for $CuInSe_2$ deposition which is more energy-intensive than the elektrodeposition method used for CdTe.

Comparison with the estimates by Hynes et al [28] of energy requirement for electrodeposited CdTe modules (GER = 275 kWh_{th}/m^2) shows on first view a good correspondence with our worst case value. However, the contributions for capital equipment and input materials are estimated quite differently (lower resp. higher) by Hynes et al. Only a further analysis of underlying assumptions may lead to an explanation of these differences and, possibly, a consensus result.

Based on our estimates the energy pay-back times which can be calculated for CdTe and CIS modules are fairly good, lower than 2.5 years. However one should note that commercial production of CdTe or CIS modules with 10% (cell) efficiency, as assumed for the worst case, has not been proven yet, while for a-Si and mc-Si modules worst case technology is commercially available.

Still, the better efficiency perspectives of CdTe and CIS cells do give them an edge over a-Si technology in energy terms.

Table 4.3: Energy requirements for CdTe/CIS solar cell modules (in kWh_{th} per m^2 cell area). (See section 4.1 for an explanation of the terms GER and PER).

	CdTe			CIS		
	worst	base	best	worst	base	best
GER input material[1] (glass, EVA)	77	50	43	77	50	43
PER (indirect[2] + direct)	100	90	70	280	220	180
GER capital	124	34	11	124	34	11
GER module (excl. frame)	301	174	124	481	304	235
Energy Pay-Back Time (in years; Netherlands)	1.6	0.6	0.4	2.5	1.1	0.7
Energy Pay-Back Time (in yr; global average)	0.9	0.4	0.2	1.5	0.6	0.4

Notes: 1) Updated GER values for glass and EVA (cf. section 5.3), therefore different from original study;
2) Indirect PER was not estimated in original study, here same value as for a-Si module assumed;

4.5 Frames and support structures

Solar cell modules may be fitted with a frame to provide a way to fasten the modules on the array support structure. In most cases such a frame consists of an aluminium profile which is fitted around the outside edges of the module. A typical frame for mc-Si modules has a weight of 0,35 kg per meter frame length, which corresponds with an extra energy requirement of resp. 175, 120 and 80 kWh_{th}/m^2 for a worst, base and best case mc-Si module[*]. This means an extra energy pay-back time under Dutch conditions of resp. 0.7, 0.4 and 0.2 years for the frame (under global average conditions resp. 0.4, 0.2 and 0.15 yr). For the worst case a-Si modules the additional energy pay back time for a frame can even be 1 year.

In general, module frame requirements can best be considered in relation to the array support structure. In a certain type of roof-top PV installations, for example, **frameless** modules may be placed on aluminium support profiles which require about 2 kg of aluminium per m^2. The Gross Energy Requirement for this support structure would be about 130 kWh_{th}/m^2 (from which a credit of 28 kWh_{th}/m^2 may be subtracted for unneeded roof tiles) [22].
Support structures for ground-based arrays may require 8-50 kg steel per m^2 module area corresponding with a Gross Energy Requirement of 55-210 kWh_{th}/m^2. Modules which are to be installed into such a support structure will in most cases also need a module frame, so that total GER values of 230-500 kWh_{th}/m^2 for frame and support may be found [25].

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[*] Assuming resp. 2.8, 2.1 and 1.6 kg of Al per m^2 cell area for the worst base and best case, as well as a reduction in energy requirements for Al production (see 4.1). The Al is assumed to be produced from 100% virgin material.

Energy requirements for cabling and power conditioning equipment are much smaller and can be neglected for a first consideration.

The considerations above show that module frames and array support structures may cause a substantial increase in the total energy requirement for a PV system and that reduction options for these system components need serious attention. One straightforward option is the use of secondary (=recycled) aluminium instead of virgin aluminium[*], resulting in a reduction of up to 80% for the aluminium components. Another attractive option may be the use of plastic instead of aluminium frames: using a polyethylene frame with twice the thickness of the Al frame may reduce the frame's energy requirement also by 80% [25].

4.6 Conclusions

Gross energy requirements for solar modules vary from ca. 175 to 400 kWh_{th}/m^2 for the base case definition. In general very good prospects exist for reduction of energy requirements by future technology developments, which in most cases are likely to be introduced for reasons of cost reduction or cell performance enhancement.

Although the energy pay-back time of the present-day mc-Si and a-Si modules (frameless) under Dutch irradiation conditions is relatively high with 3.8 years respectively 4.6 years, it is still considerably shorter than the expected technical lifetime of the module (15-30 years). Moreover, probable technology developments should result in base case energy pay-back times which are much shorter, namely resp. 1.2, 1.2, 0.6 and 1.1 years for mc-Si, a-Si, CdTe and CIS modules (also under Dutch irradiation conditions).

Frames and support structures can add substantially, in the order of 100-500 kWh_{th}/m^2 to the total energy requirement of a PV system, in other words frames and supports may double the energy pay-back time of the PV system. Therefore serious attention is necessary for designs of array support structures which have a low energy requirement.

Finally it should be noted that there is still considerable uncertainty on the energy requirements of solar cell production and that some studies give very different results for certain process steps. For example, Palz and Zibetta [27] give much more optimistic GER values for mc-Si and a-Si modules, while on the other hand the estimates by Hagedorn [16, 17] are more or less in line with our values. The estimates which we present in this report are based on the sources which we viewed as the most reliable. Still, it seems worthwhile to aim at a greater consensus in this area so that a clear message on energy requirements and energy pay-back times of PV technology may be conveyed to policy makers and the public in general.

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[*] Use of 100% secondary alumnium would reduce the energy requirement for the frame by about 80%.

5 Material flow analysis

5.1 Introduction

For all four cell types we have analysed material flows and estimated emissions due to module production. In these analysis we have considered only direct material inputs, so the production of commodities, like aluminium and glass, and capital goods was not taken into account.
A comprehensive overview of all material requirements and emissions is impossible in the context of this summary report, therefore we will highlight a few notable aspects per cell type, beginning with the issue of resource depletion.

5.2 Resource depletion

In order to evaluate resource depletion impacts we will estimate the material requirements if 5% of the current world electricity production (1 TWy/y) is supplied by means of one specific type of solar cell modules (base case variant). This would mean that ca. 13 GWp of solar cell modules have to be produced annually. The corresponding material requirements will be compared with current production levels and estimated reserves.
As no recycling technologies are currently available for solar cell modules, the effect of recycling of resource materials will not be considered here (cf. section 5.4).

mc-Si modules

Quartz sand, the primary feedstock material for production mc-Si cells, is very abundant so on this point resource availability will probably never be an issue. One point of concern, however, is the consumption of silver for the contacts. It was estimated that about 50 g of silver is required per m^2 cell area, so that supply of 5% of mondial electricity consumption would require 4 kton of silver per year or 30% of the current silver production (table 5.1). So reduction of silver use in the contacts is of importance.
Probably a reduction of silver use will also be pursued for reasons of cost reduction. In fact, the silver requirement in our best case mc-Si modules is only 7% of the base case requirement.

a-Si modules

No resource availability problems whatsoever are expected for a-Si modules.

CdTe and CIS modules

For production of base case CdTe modules about 60 ton/GWp of both Cd and Te is required. In view of current production levels and estimated reserves (table 5.2) the supply of cadmium will not be a bottleneck. The supply of tellurium, however, may become a problem if CdTe modules are to contribute significantly to the world electricity supply. Te is mainly produced as byproduct of copper, and as such the production capacity may be limited to 400 ton maximum.

For base case CIS module production about 70 ton of indium and 125 ton of selenium is needed. Current indium production is very small (140 ton/y) and the maximum production capacity as a by-product of zinc winning may be limited to 1000 tons. Also the mondial reserves may be depleted within a few years if CIS modules are to supply 5% of the world electricity production. Selenium supply, on the other hand, will be much less problematic.
The resource requirements for the worst and best case CdTe and CIS modules can be found by multiplication with a factor 5 resp. 0.35.

In view of these resource considerations recycling of the metals in CdTe and CIS modules will become a point of major importance if these module types are to be implemented on a large scale (see 5.5).

Table 5.1: Resource material requirements for base case PV module production compared to current production levels, maximum production capacities and estimated reserves. Material requirements are given for 13 GWp/y module production which allows 5% of mondial electricity production to be supplied. For Cd, Te, In and Se estimates are given for maximum production of the material *as a by-product* of zinc or copper winning.

Cell type	resource material	requirement for 5% electr. prod. by PV (kton/y)	mondial production[1] (kton/y)	max. production as by-product (kton/y)	reserve base[1] (kton)
mc-Si	Si	120	3600	n.a.	large
	Ag	4	13.7	n.a.	420
a-Si	Si	0.3	3600	n.a.	large
CdTe	Cd	0.8	20	30	970
	Te	0.8	0.5	4	38
CIS	In	0.9	0.14	1	5
	Se	1.6	1.8	10	130

Notes: 1) Source: US Bureau of Mines, 1992 [29].

5.3 Emissions to the environment

General remarks

For all module types the material balance is dominated by the bulk type materials used for module encapsulation (glass, EVA). Also waste emissions consisting of rejected or decommissioned modules form an important contribution (in mass terms).

For the thin film type of modules (a-Si, CdTe, CIS) the emission of tin to the water resulting from the TCO deposition process, is a point of attention.

With respect to different cases one may remark that, going from worst to best case, the general trend for increased material efficiency will mostly lead to decreasing emissions per unit cell area. Furthermore emissions on energy-basis, which are more relevant in comparisons with other energy technologies, will of course benefit from the increasing cell performance.

mc-Si modules

Environmentally relevant substances which may be released in multicrystalline silicon PV module production are fluorine, chlorine, nitrate, isopropanol, SO_2, CO_2, respirable silica particles and solvents. Emissions of (non-energy-related) CO_2 and SO_2 from mc-Si module production are mainly caused by the carbothermic silica reduction process. Standard measures, like the use of low-sulphur fuel and desulphurization of flue gases can may significantly reduce the SO_2 emissions.

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 resulting from neutralizing etching and texturing solutions and flue gases. Compared on an energy basis the Cl- and F-emissions for the base case module are estimated to be resp. 89,000 and 1,500 kg/TWh, which is 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 and control measures.

Also care should be taken to prevent accidental emissions of CF_4, because this gas has a very high Global Warming Potential.

The possibilities for reuse of production waste, e.g. silicon wafers and silicon carbide, should be investigated.

The differences between respective cases for mc-Si modules are not remarkable, although emissions will decrease somewhat due to increased material efficiency.

a-Si modules

Apart from the remarks made above with respect to (thin-film) modules in general there are little or no significant emissions to be expected from a-Si module production, use and decommissioning. The emissions from the silane production process contribute only very little to the total emissions and can be neglected.

Regarding the comparative emissions of the three a-Si cases we can conclude that the trends toward improved material utilization and lower glass content of the module which may be expected from current R&D efforts, will also contribute to a further reduction of the environmental impacts of a-Si module production.

In total, we can say that for the assumed system boundaries and assuming proper emission control measures large-scale production of a-Si modules will not result in any serious environmental emission.

CdTe and CIS modules

As stated above we have only considered the material flows of the heavy metals contained in CdTe and CIS modules. A first point to note in this respect is that CdTe or CIS modules contain only a relatively small amount of heavy metals, for example base case CdTe modules contain ca. 6 g of cadmium per m^2 module area. By comparison, a single NiCad penlight battery contains 2.5 g of cadmium. If we consider both products as an energy supplier (although NiCads are obviously not a real energy source) then we find that the amount of cadmium contained in the base case CdTe module is about 0.001 g per kWh supplied (0.006 g/kWh for the worst case), while the NiCad battery requires about 5 g Cd per kWh supplied.

For our assessment of environmental emissions we will focus on the estimated emissions of cadmium resp. selenium to the atmosphere which are summarized in tables 5.2 and 5.3. We can see that in the base case the emissions mainly occur in the resource mining (and refining) and in the module utilization phase. From worst to best case the emissions differ by roughly a factor of 10, reflecting the uncertainty regarding emission rates for future technology cases. Emissions of selenium are considerably higher than for cadmium because of less stringent emission control measures. It should be noted that there is some uncertainty in the assumptions underlying the emission estimates for the module utilization and decommissioning phases.

Also it is important to note that the risks of cadmium (or selenium) releases to the environment from the utilization and decommissioning phases are very much dependant on the type of encapsulation that is chosen for the module. Experimental tests suggest that releases from modules with a double glass encapsulation are considerably lower than for modules without a glass cover at the backside [21, 30]. Unfortunately CdTe modules which are presently offered on the market often do not have a back glass cover.

Table 5.2: Atmospheric **cadmium** emissions from the life cycle of CdTe modules and from coal-fired electricity generation.

	worst	base	best
Mining (mg/m^2)	11	0.9	0.2
Module production (mg/m^2)	8	0.4	0.05
Utilization[1] (mg/m^2)	1.8	1.1	0.5
Decommissioning[2] (mg/m^2)	1.8	0.2	0.005
Total emission (mg/m^2)	22.6	2.6	0.8
Emission per unit energy[3] (g/GWh)	11.8	0.5	0.1

Cd emission from coal plant[4] (g/GWh)	0.6-10
Cd emission from coal gasification plant (g/GWh)	0.06-1

Notes: 1) Over resp. 15, 25 or 30 year module life time; assumptions different from original study (see table 3.9, note 1).

2) Different from original study (see table 3.9, note 3).

3) Assuming global average irradiation, values are factor 1.7 higher for Dutch irradiation conditions.

4) Estimate for modern coal plant in the Netherlands.

Table 5.3: Atmospheric **selenium** emissions from the life cycle of $CuInSe_2$ modules and from coal-fired electricity generation.

	worst	base	best
Mining (mg/m^2)	260	19	3.6
Module production (mg/m^2)	210	11	1.5
Utilization[1] (mg/m^2)	25	15	6.0
Decommissioning[2] (mg/m^2)	5	0.5	0.07
Total emission (mg/m^2)	500	45.5	11.2
Emission per unit energy[3] (g/GWh)	260	8.9	1.8

Se emission from coal plant[4] (g/GWh)	70
Se emission from coal gasification plant (g/GWh)	60

Notes: 1) Over resp. 15, 25 or 30 year module life time; assumptions different from original study(see table 3.9, note 1);
2) Different from original study (see table 3.9, note 3).
3) Assuming global average irradiation, values are factor 1.7 higher for Dutch irradiation conditions.
4) Estimate for modern coal plant in the Netherlands.

In order to put these emission estimates into perspective we can compare them with the emissions of cadmium and selenium from coal-fired electricity generation which has been estimated at 0.6-10 g/GWh resp. 70 g/GWh for a modern coal power plant in the Netherlands. For a plant based on coal gasification technology, however, emissions are lower, namely 0.06-1 g/GWh for Cd and 60 g/GWh for Se.

We can therefore conclude that the atmospheric Cd emissions for the base case CdTe module of 0.5 g/GWh (0.9 g/GWh in the Netherlands) are lower than those of a modern coal power plant, but may be higher than for a coal gasification power plant. With regard to CIS modules the base case Se emissions to the air are significantly lower than Se emissions both from conventional coal plants and from coal gasification plants.

An important point to note in this respect is that coal-fired plants have many more emissions (a.o. SO_2, NO_x, Cl, F, B, Cr, Hg, Pb) which are often larger than the Cd or Se emissions. For CdTe or CIS modules, on the other hand, cadmium respectively selenium will be one of the few environmentally relevant emissions.

A second way to put the results above into perspective is to compare the estimated emissions with the total emissions of Cd or Se from all existing economic activities. Consider for example a situation where 5% of the current Dutch electricity production (ca. 80 TWh/yr) would be generated by base case CdTe or CIS modules. The resulting Cd and Se emissions from this activity would then be 3.5 kg/yr respectively 60 kg/yr, which is equivalent to 0.2% resp. 0.6% of the current total emissions of Cd and Se in the Netherlands.

The evaluation whether emissions as estimated above may be acceptable for society or not remains a difficult problem and in the end it is a political choice. However, it seems to us that the results above give no reason for immediate concern, although it would be good if the range of uncertainty could be reduced.

5.4 Module decommissioning and recycling options

After their useful lifetime the solar cell system will be dismantled and resulting waste streams will have to treated in a responsible manner. In this section we will consider some issues of module waste management and discuss recycling possibilities.

mc-Si modules

Mc-Si modules consist mainly of glass (78 wt. %), with smaller fractions of EVA (10 wt.%), polyester (7%) and silicon (4 wt. %) all rather harmless materials. However, small amounts of silver (0.4 wt. %) and copper (0.3 wt.%) for the worst case module are also in the module waste in concentrations which are just below the threshold value for "Dangerous Waste" (0.5 wt%) according to Dutch environmental regulations.

As yet there is no commercial process available for recycling of mc-Si modules. Recycling of the module cover glass should be possible if methods are developed to separate it from the EVA and other module components. Recycling of module glass with adherent EVA will meet some restrictions (see below under a-Si modules).

Methods for reclaiming the silicon wafers from a (rejected) module have been investigated [31], but to our knowledge they are not commercially applied up to now.

a-Si modules

a-Si modules consist mainly of glass and can therefore be used as feedstock for secondary glass production (glass recycling). Recent experiments have shown that the only restrictions are the modules should mainly be used for production of coloured packing glass and that the fraction of module waste in the total feedstock should remain below 10%. These restrictions, however, would not pose any serious limitations on future a-Si module deployment [32].

Also it has been demonstrated that it is technically possible to re-use a glass substrate (including the TCO layer) after etching off the a-Si and back contact layers from a *non-encapsulated* module. This approach may be interesting for the reprocessing of rejected modules in a module production plant [32].

CdTe/CIS modules

The heavy metal content of CdTe and CIS modules would require them to be treated as "Dangerous Waste" under the existing regulations in the Netherlands. On the other hand,

at least one type of commercially available CdTe modules has been shown to meet the proposed EC regulations for waste disposal in land fill sites [33].

The heavy metal content of CdTe/CIS modules makes them less attractive as feedstock for secondary glass production.

One viable option for disposal is to feed the modules into non-ferrous smelters [14]. Although no estimates are available at this time, it would seem that the total volume of module waste which can be disposed of in this way is rather limited, so that it is probably not a long-term solution.

If large scale deployment of CdTe or CIS modules is considered then the recovery of the heavy metals from the module waste will probably be required, from the viewpoint of both waste management and resource management (cf. 5.1). It appears that hydrometallurgical methods offer the best prospects for such a metal recovery process, although effective extraction of the metals from an encapsulated module may be problematic [14, 34]. Also the low concentration of metals would probably lead to added cost for the recycling process.

5.5 Conclusions

From our analyses we conclude that for the immediate future and within the considered system boundaries there are no reasons for concern regarding the material requirements and emissions of solar cell modules. Only if large scale deployment of modules - with annual production levels of several GW's - becomes probable there are some points which need closer attention, namely:

- resource depletion of silver (mc-Si modules);
- resource depletion of indium (CIS modules)
- waste management and recycling possibilities for decommissioned modules (mc-Si, CdTe, CIS);
- cumulative fire-induced emissions from CdTe and CIS modules.

Although there is still a considerable range of uncertainty in our emission estimates the risks from cadmium or selenium use in CdTe respectively CIS modules seem acceptable in comparison with some existing products or services like NiCad batteries or coal-fired electricity production.

6 Health and safety risks

In this chapter we will shortly review occupational health and safety risks and external safety risks. Public health risks are not discussed here because they are a consequence of the emissions discussed in the previous chapter. Moreover, the estimation of public health risks from emission data was not part of our study scope because it is a very complex task.

We will focus here on risks resulting from module production. One general point of attention for module installation and use are the electrical shock hazards. However, with a proper design of the electrical lay-out so that dc voltages are either kept below 110 V or higher voltages are properly shielded, no serious risks should result.

6.1 mc-Si module

No serious health and safety risks are expected for workers involved in mc-Si module production. Exposure to etchants like HF, HNO_3 and HCl and exposure to silane or other hydrides poses a moderate risks, which should be controllable within normal safety procedures. External safety risks seem small for mc-Si module production, only the storage of silane should be performed with the proper safeguards (see under a-Si below). Silane use is, however, much smaller than for a-Si module production.

6.2 a-Si modules

Silane, the primary feedstock gas in a-Si module production, is a highly flammable gas which may ignite spontaneously in air. Because self-ignition does not always occur, large gas clouds may build up which can cause a severe explosion. Proper control measures are therefore necessary to prevent these situations.

Moskowitz and Fthenakis [13] review various control measures for storage and handling of hazardous gasses in a-Si module production facilities. However, no detailed risk analysis are known of installations where silane and the other hydrides are handled in the amounts needed for a 10-50 MWp PV production capacity. Therefore, reliable statements on the safety risks of large-scale a-Si production facilities cannot be made with the available data.

6.3 CdTe and CIS modules

First of all one should note that CdTe and CIS contain only little toxic material (see 5.2.3). Moreover the toxicity of *ingested* CdTe appears to be relatively low because of its low solubility [35].

Obviously, the exposure to cadmium of workers in a module production plant should be kept as low as possible. Current practices in such plants have proven to be more than sufficient in this respect [33], so there appears to be no reason for concern about occupational health risks if proper measures have been taken.

Recent studies have furthermore shown that there is negligible risk of dangerous exposure to cadmium from a stock of CdTe modules during a fire [33]. This should also rule out acute health risks due to fires in roof-top PV installations.

Regarding selenium the exposure limits for air-borne material are a factor 10 higher than for cadmium compounds so it should be relatively easy to keep occupational Se exposures at acceptable levels. Furthermore the toxicity of elementary selenium appears to be moderate (up to now toxicity data on $CuInSe_2$ itself are very limited [36]); therefore the main health risk from CIS appears to be exposure to SeO_2 which may be formed at temperatures above 350 ^{o}C.

A major risk factor of CIS module production can be the use of hydrogen selenide, which may be used as a feedstock gas in the $CuInSe_2$ deposition process. An accidental release of 25 kg

(=one typical gas container) of H_2Se can lead to dangerous exposure levels in an 40 m x 3000 m area. However, there are alternative CIS deposition methods available which do not require the use of H_2Se.

6.4 Conclusions

The only significant risks regarding occupational health and safety and external safety are found in the storage and handling of explosive and/or toxic gasses, i.c. silane in a-Si production and H_2Se in certain CIS deposition processes.

With proper safety measures in place silane risks seem to be well manageable, but still the issue of silane storage at large-scale a-Si module production facilities (>10 MWp/yr) remains a point of attention. Regarding CIS module production it is advisable to avoid deposition methods involving the use of hydrogen selenide gas.

7 Summary and Conclusions

The environmental aspects of four major solar cell technologies have been reviewed with special attention for future expected technology developments. Cell technologies investigated are multicrystalline silicon (mc-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and $CuInSe_2$ (CIS). The following aspects were considered: energy requirements and energy pay-back time, material requirements and resource depletion, environmental emissions, waste handling, possibilities for recycling of modules, occupational health and safety and external safety.

Although the energy pay-back time of the present-day mc-Si and a-Si modules is relatively high, around 4 to 4.5 years for frameless modules under Dutch irradiation conditions, this pay-back time is still considerably shorter than the expected technical lifetime of the module (15-30 years). Moreover, very good prospects exist for reduction of energy requirements by future technology developments, resulting in energy pay-back times well below 1.5 years for all module types (under Dutch irradiation conditions; below 1 year for global average irradiation).
It is remarkable that thin film technologies (a-Si, CdTe, CIS) do not score significantly better (in some cases even worse) as wafer-based mc-Si technology. This mainly caused by the superior efficiency of mc-Si cells.
Note that frames and support structures can add substantially to the energy requirements and may double the energy pay-back time of the total PV system (compared to modules only). Therefore serious attention is necessary for designs of array support structures which have a low energy requirement.

From our analyses of the material flows we conclude that for the immediate future (and within the considered system boundaries) there are no reasons for concern regarding the material requirements and emissions of solar cell modules. Only if large scale deployment of modules - with annual production levels of several GW's - becomes probable there are some points which need closer attention, namely:

- resource depletion of silver (mc-Si modules);
- resource depletion of indium (CIS modules);
- waste management and recycling possibilities for decommissioned modules (mc-Si, CdTe, CIS);
- cumulative fire-induced emissions from CdTe and CIS modules.

Although there is still a considerable range of uncertainty in our emission estimates the risks from cadmium or selenium use in CdTe respectively CIS modules seem acceptable in comparison with some existing products or services like NiCad batteries or coal-fired electricity production.

Regarding occupational health and safety and external safety the only significant risks are found in the storage and handling of explosive and/or toxic gasses, i.c. silane in a-Si production and H_2Se in a certain CIS deposition process.
With proper safety measures in place silane risks seem to be well manageable, but use of hydrogen selenide gas should be avoided.

Finally, table 7.1 presents a qualitative comparison of these cell types on the aspects mentioned above.
We can see that there is not one single cell type that scores good or excellent on all considered aspects, although future a-Si technology, seems to be the most "environmentally friendly" technology, with mc-Si as a good second. CIS and CdTe score less well because of problems related to the use of heavy metals, some of which are rather scarce. However, these problems should not be considered as a major bottle-neck for the immediate future. Therefore they should

not be used as a reason for ruling out one or more of the considered solar cell technologies from further R&D efforts.

Table 7.1: Qualitative comparison of the investigated solar cell technologies. *Present* respectively *future* indicates the assumed technology status with regard to module production, emission control technology and recycling. Scores for present technology are based on the worst case results described in previous chapters, while scores for future technology are based on both base case (70%) and best case results (30%). Note that effects of increasing production volumes, leading for example to increasing emissions, are *not* considered between present and future technology.

	mc-Si		a-Si		CdTe		CuInSe$_2$	
	present	future	present	future	present	future	present	future
Energy Pay-Back[1]	+/-	++	-	++	++	+++	+	+++
Resource depletion	+/-	+	++	++	+	+	-	-
Emissions	+	+	++	++	-	+/-	+/-	+
Health & Safety[2]	+	+	+/-	+/-	+	+	+/-	+/-
Recyclability	-	+/-	++	++	-	-	-	-

Notes: 1) - = 4-5 yr, +/- = 3-4yr, + = 2-3 yr, ++ = 1-2 yr, +++ = 0-1 yr under Dutch irradiation conditions;
2) Refers to occupational health & safety, and to external safety aspects, not to public health aspects.

All in all we conclude from our investigations that - at least for the immediate future - there are no major bottlenecks from environmental point of view for the considered solar cell technologies. However, during module production substances are used which may be harmful for workers, the public or the environment. Therefore manufacturers should take proper measures to avoid harmful exposures or emissions.

Points which deserve further attention both from manufacturers and researchers are: the energy requirements of modules (and module frames and supports), the use of heavy metals, gas safety issues and module recycling possibilities.

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Appendix: Energy production by the PV modules

Below we give the assumptions and the results for the energy production of the different types of PV modules under different irradiation conditions. The yearly electricity output is calculated as the product of cell efficiency, System Performance Ratio and irradiation. Multiplication with the module lifetime gives production over the lifetime; division of the yearly electricity output by the mean conversion efficiency from primary to electrical energy gives the yearly saving of primary energy (fuel energy).

Table A.1: Assumptions for calculation of energy production by PV modules.

	worst	base	best
System Performance Ratio	0.75	0.80	0.85
Module lifetime (yr)	15	25	30
Efficiency of conversion from primary energy to electricity	0.39	0.42	0.45
Global average irradiation (kWh/m^2/yr)	1700	1700	1700
Netherlands irradiation (kWh/m^2/yr)	1000	1000	1000

Table A.2: Energy production data for **multicrystalline silicon** modules

		unit	worst	base	best
cell efficiency			13%	16%	18%
global average irradiation	yearly electr. prod.	kWh$_e$/m^2/yr	166	218	260
	electr. prod. over lifetime	kWh$_e$/m^2	2,490	5,450	6,540
	yearly primary energy saving	kWh$_{th}$/m^2/yr	425	518	578
Netherlands irradiation	yearly electr. prod.	kWh$_e$/m^2/yr	98	128	153
	electr. prod. over lifetime	kWh$_e$/m^2	1,470	3,200	4,590
	yearly primary energy saving	kWh$_{th}$/m^2/yr	250	305	340

Table A.3: Energy production data for **amorphous silicon** modules.

		unit	worst	base	best
cell efficiency			6%	10%	15%
global average irradiation	yearly electr. prod.	kWh$_e$/m^2/yr	77	136	217
	electr. prod. over lifetime	kWh$_e$/m^2	1,155	3,400	4,080
	yearly primary energy saving	kWh$_{th}$/m^2/yr	196	324	482
Netherlands irradiation	yearly electr. prod.	kWh$_e$/m^2/yr	45	80	128
	electr. prod. over lifetime	kWh$_e$/m^2	675	2,000	3,840
	yearly primary energy saving	kWh$_{th}$/m^2/yr	115	190	283

Table A.4: Energy production data for **CdTe and CIS** modules.

		unit	worst	base	best
cell efficiency			10%	15%	18%
global average irradiation	yearly electr. prod.	$kWh_e/m^2/yr$	128	204	260
	electr. prod. over lifetime	kWh_e/m^2	1,920	5,100	6,120
	yearly primary energy saving	$kWh_{th}/m^2/yr$	327	486	578
Netherlands irradiation	yearly electr. prod.	$kWh_e/m^2/yr$	75	120	153
	electr. prod. over lifetime	kWh_e/m^2	1,125	3,000	4,590
	yearly primary energy saving	$kWh_{th}/m^2/yr$	192	286	340