ECN-RX--06-005

Environmental life cycle inventory of crystalline silicon photovoltaic module production

M.J. de Wild-Scholten
E.A. Alsema (Utrecht University)

Presented at Materials Research Society Fall 2005 Meeting, November 2005, Boston, USA

November 2005

Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production

Mariska J. de Wild-Scholten, m.dewild@ecn.nl
Energy research Centre of the Netherlands ECN, Unit Solar Energy
Westerduinweg 3, P.O. Box 1, NL-1755 ZG Petten, The Netherlands

Erik A. Alsema, e.a.alsema@chem.uu.nl
Department of Science, Technology and Society
Copernicus Institute, Utrecht University
Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

ABSTRACT

Together with 11 European and US photovoltaic companies an extensive effort has been made to collect Life Cycle Inventory (LCI) data that represents the status of production technology for crystalline silicon modules for the year 2004. These data can be used to evaluate the environmental impacts of photovoltaic solar energy systems.
The new data covers all processes from silicon feedstock production via wafer- and cell- to module manufacturing. All commercial wafer technologies are covered, i.e multi- and mono-crystalline wafers as well as ribbon technologies. For monocrystalline silicon wafer production further improvement of the data quality is recommended.

INTRODUCTION

Reliable data on the environmental impact of PV module manufacturing have been rather scarce for the last 10-15 years. The only extensive data collection based on production data was published in [1] and was based on technology from the late 80's. Consequently, life cycle assessment [2-4] and external cost studies [5] were often based on the older data set that does not reflect the technological progress made over the past decade.

GOAL

Together with 11 European and US photovoltaic companies an extensive effort has been made to collect LCI data that represents the status of production technology for crystalline silicon modules. This module type was used in 94% of the 1256 MWp of the produced solar cells in 2004 [6].
The actual results in terms of environmental impact, based on the data in this paper, are published elsewhere [7].
This effort was conducted in the framework of the CrystalClear project; a large European Integrated Project focusing on crystalline silicon technology, co-funded by the European Commission and the participants.

SCOPE

The new data covers all processes from silicon feedstock production via wafer and cell to module manufacturing. All commercial wafer technologies are covered, i.e. multi- and mono-crystalline wafers as well as ribbon technologies (see figure 1)
All data were collected in the period September 2004-November 2005 and are representative for the technology status in 2004, although for mono-crystalline silicon wafer production further improvement of the data quality is recommended.

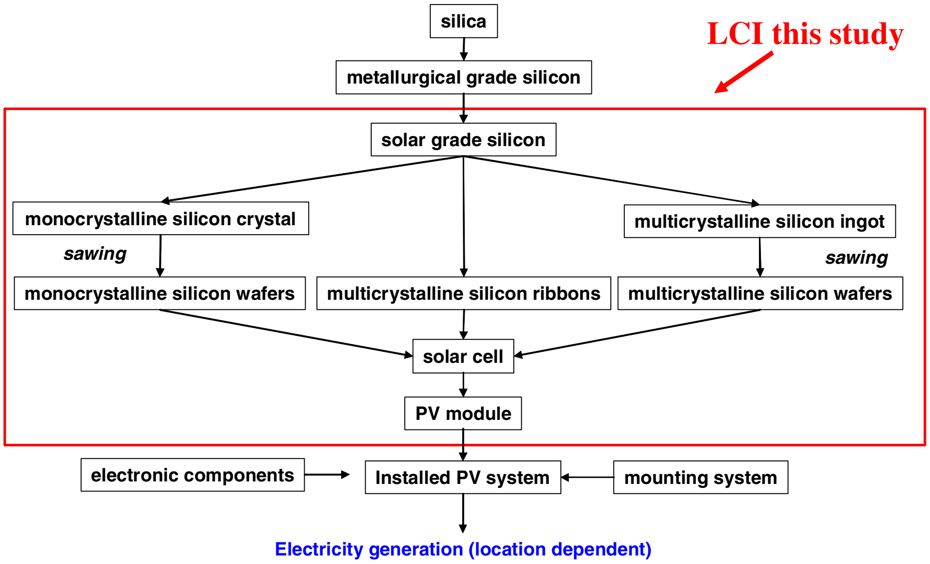

Figure 1. System boundary for Life Cycle Inventory

METHODS

The data collection took quite some time, because many companies had to make a special effort to collect the requested data. The life cycle inventory data are based on real measured data from production lines. Companies mostly consider material- and energy consumption data as confidential information. Because one of our aims was to prepare a publishable set of LCI data (i.e. data on material and energy inputs, as well as emissions per process step), we tried to get at least three data suppliers for each process step and process technology (e.g. multi-Si crystallization and wafering). In this way we could generate average LCI data without disclosing proprietary information.
This goal was realized to a large extent, but some cells of the process/technology matrix are less well covered so that we had to make use of existing data from literature (see table 1).
Also we needed to aggregate the process data into 4 main process steps: 1) silicon feedstock 2) crystallization and wafering 3) cell processing 4) module assembly.

Table 1. Overview of used data sources for the LCI data set, the number indicates the number of companies that have supplied data.

Wafer technology / Process step	**Multi Si**	**Mono Si**	**Ribbon Si**
Si feedstock production	1 + literature		
Crystallization + wafering	3 + equipment manufacturer	1 (1999) + update 2004 + literature	2 + 1 pilot
Cell processing	4 multi-Si + 1 mono-Si		
Module assembly	2 + material suppliers		

RESULTS

The collected LCI data are presented in tables I-VI for the respective process steps outlined in figure 1. They are also available as Excel file on http://www.ecn.nl/library/reports/2006/c06002.html.
For the production of high-purity polycrystalline silicon from metallurgical-grade silicon, we only considered processes that are specifically dedicated to production of silicon for PV applications. This material is sometimes called "solar-grade" silicon but the same name is also used for entirely new process routes. The processes we considered employ a modified version of the Siemens deposition reactor ("modified Siemens"), which results in a lower energy consumption than the conventional Siemens process. We did not include "scrap silicon" from electronic-grade silicon production because the market share of this material has decreased to a mere 5% in 2005 [11]. This also avoids the difficult issue of allocation on inventory data between "full-spec"and "off-spec" silicon (cf. [2,10]). We were able to obtain specific LCI data from one producer of polycrystalline silicon, which we aggregated with estimated data for another producer. The latter estimate was based on literature data for the standard Siemens process [2] together with an indication of achieved energy reductions for the modified-Siemens process as indicated by the manufacturer. The mix of electricity supply that we include in the presented data set is representative for the actual production locations of these two producers. It should be noted, however, that the specific choice of electricity supply sources for silicon production can have a considerable influence on the results of impacts analysis of the PV module. Therefore it is recommendable to perform a number of sensitivity analyses with different electricity supply mixes for this process. The LCI data are average numbers over old and new Siemens reactors. The newer reactors have substantially lower energy consumption than those of 10-15 years old. Furthermore, the new fluidized bed reactor (FBR) process, currently being developed, may cut the electricity consumption by upto 90%.

The separate processes of crystallization and wafer cutting had to be aggregated into one process data sheet for reasons of data availability and confidentiality. For this process step we did discern between the three main wafer technologies, namely multicrystalline, monocrystalline and ribbon technology.

Regarding crystallization and cutting of multi-crystalline silicon we had data sets from three different facilities. We observed significant differences between these sources with respect to energy consumption. This is probably due to the different ages of the production installations, where the more modern facilities have significantly lower energy consumption. For material consumption the differences were less important.

Also for the ribbon growth process we had data sets from three facilities. Among the ribbon growing technologies, though, there is one process (RGS), which is still in pilot stage. For the purpose of data aggregation, we considered this as a commercial scale operation. Nonetheless, the aggregated process data for ribbons can be considered as representative for today's technologies.

For monocrystalline silicon Czochralski crystal growing there is unfortunately quite some uncertainty in the data. We did use data for crystal growing as measured some five years ago [8], combined with updates on subsequent process improvements leading to reduced energy consumption [9]. The older data we assumed to be representative for producers in Eastern-Europe and Russia, while the newer process data probably reflects present-day production conditions in Western-Europe/USA. A third source was data from literature [2] for "electronic" wafers, which data was reasonably consistent with the older process data from [8]. Because of the remaining uncertainties on direct and overhead energy consumption and on the yield figures, and in view of the relative importance of this process step, we would like to improve further on the data accuracy and representativity.

With regard to cell processing we did not distinguish between multi-, mono- and ribbon technology, because the observed differences were small (in terms of material or energy inputs). Here we obtained data from 5 different sources.

For module assembly, our LCI data are based on a module of 6x12 cells of 125 mm x 125 mm (total module size 1.25 m^2). The number of independent data sources for the process of module assembly was lower than for other processes but we do not expect that this increases the uncertainty much as this process is reasonably standardized. Moreover, because material consumption is the most important input in this process (not energy consumption), the quantity of which is largely determined by the module area and yield, there will not be much variation in LCI data between manufacturers.

CONCLUSIONS

A full set of Life Cycle Inventory data for the production of crystalline silicon solar cell modules has been collected and presented. The data set is representative of the production technology in 2004, mainly for manufacturers in Western Europe. For the first time an LCI data set is now publicly available, based on actual manufacturer's data for all relevant processes and which also covers silicon ribbon technologies.

The largest remaining data uncertainty exists for the production of monocrystalline silicon crystals by means of the Czochralski process. For this we hope to be able to improve data quality in the future in close cooperation with industry. Also analysts should be aware of the large influence that the electricity supply mix for the solar grade silicon process will have on final impact results.

ACKNOWLEDGEMENTS

This research was conducted within the Integrated Project CrystalClear and funded by the European Commission under contract nr. SES6-CT_2003-502583. The authors gratefully acknowledge the help of V. Fthenakis (Brookhaven National Laboratory), R. Lüdemann (Deutsche Cell), A. Müller, K. Wambach (Deutsche Solar), M. Jansen, A. Schönecker (ECN), B. Williams (Evergreen Solar), P. Nasch (HCT Shaping Systems), V. Escudero, P. Sánchez-Friera (Isofoton), N. Le Quang (Photowatt), E. Sauar, R. Glenne (REC/Scanwafer), A. Metz (Schott Solar), S. Zijlstra (Shell Solar, Gelsenkirchen), W. Trumm (Shell Solar, Munich) and T. Jester (Shell Solar, Camarillo). Without their effort we would not have been able to present any of the results of this paper.

REFERENCES

[1] Hagedorn,G. and E.Hellriegel (1992): Umweltrelevante Masseneinträge bei der Herstellung verschiedener Solarzellentypen; eine vergleichende Analyse konventioneller und ausgewählter neuer Verfahren unter Berücksichtigung der Einsatzstoffe und Prozeßketten sowie der Entsorgungs- und Recyclingmöglichkeiten - Endbericht - Teil I: Konventionelle Verfahren; Forschungsstelle für Energiewirtschaft (FfE), München, Germany, 051.24: 220 p;
[2] Jungbluth,N. (2005): Life cycle assessment of crystalline photovoltaics in the swiss ecoinvent database; *Progress in Photovoltaics: Research and Applications* **13** (**5**): 429-446;
[3] Frankl,P., A.Corrado and S.Lombardelli (2004): ECLIPSE Environmental and ecological life cycle inventories for present and future power systems in Europe. Photovoltaic (PV) systems. final report; -200 p.;
[4] Gürzenich,D. and R.Corradini (2004): Lebenszyklusinventare ausgewählter zukünftiger Stromerzeugungstechniken, Arbeitspapier zu Arbeitspaket 3, Erstellen von Sachbilanzen für die Stromerzeugung mit Photovoltaik; VDI-Gesellschaft Energietechnik, Germany, ISBN 3-931384-50-0;
[5] Rabl,A. and J.Spadaro (2004): Externalities of Energy: Extension of accounting framework and Policy Applications. Final technical report; 49 p.;
[6] Schmela,M. (2005): Market survey on global cell and module production in 2004. Super sonic solar market; *Photon International* **March**: 66-82;
[7] Alsema, E.A and de Wild-Scholten, M.J. (2005) Environmental Impact of Crystalline Silicon Photovoltaic Module Production, *Proceedings of this Conference*;
[8] Knapp,K. and T.Jester (2001): Empirical investigation of the energy payback time for photovoltaic modules; Solar Energy 71 (3): 165-172;
[9] Jester,T.L. (2002): Crystalline silicon manufacturing progress; Progress in Photovoltaics: Research and Applications 10 (2): 99-106;
[10] Alsema, E.A., P. Frankl, and K. Kato (1998), Energy Pay-back Time of Photovoltaic Energy Systems: Present Status and Prospects, 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, 6-10 July, 2125-2130;
[11] Rogol, M. (2005) Silicon and the solar sector. Mapping a new world; presentation at the 2nd Solar Silicon Conference, Munich, Germany, 11 April 2005.

Table I. Life Cycle Inventory data for the production of polycrystalline solar grade silicon feedstock

Name	**High purity polycrystalline silicon, feedstock material for crystalline silicon ingots (Poly-Si)**
Time period	2004
Geography	Europe, Western and North America
Technology	Mixed data
Representativeness	Average of data from one company and estimated data from another company based on literature data
Collection method	Data collection by factory representative + literature data.
Data treatment	
Comment	Production with Siemens process either from $SiHCl_3$ or SiH_4. Partly with standard Siemens process and partly with modified Siemens ("solar grade") at reduced electricity consumption. Mix of electricity supply in accordance with actual conditions at considered production locations.

Products	**Unit**	**Amount**	**Comment**
Polycrystalline silicon, Siemens process	kg	1.00	high purity, with specifications applicable for photovoltaic industry
Materials			
MG-silicon	kg	1.13	metallurgical grade silicon
Inorganic chemicals, unspecified	kg	2.00	mix of NaOH, HCl and H_2
Heat from natural gas	MJ	185	for process heat
Electricity/heat			
Electricity, from combined cycle plant, gas-fired	kWh	45	actual sources of electricity can vary with considered production location
Electricity, hydropower	kWh	65	mix of reservoir and run-of-river hydro
Emissions to air			
			N.B.: emissions from natural gas combustion not included here yet!

Table II. Life Cycle Inventory data for the production of monocrystalline silicon wafers from polycrystalline silicon feedstock

Name	**mono-crystalline silicon wafer from poly-Si**
Time period	2004
Geography	North America + Europe, Western + Asia, former USSR
Technology	Mixed data
Representativeness	Estimated data, partly based on data from one company (but with many unclarities) supplemented with literature sources and many own estimates.
Collection method	

Data treatment	Averaging over 3 assumed production locations.
Comment	Includes both Czochralski crystal pulling and wafer cutting processes. Wafer thickness 300 um. The process for internal recycling of silicon is NOT included in the process data, external recyling of sawing slurry is not accounted either. The amount of poly-silicon includes virgin AND recycled silicon.

Products	**Unit**	**Amount**	**Comment**
mono-Si wafer	m^2	1.00	typical wafer: 125x125 mm^2 (0.0156 m^2), semisquare, thickness 300 um
Materials			
SOLIDS			
poly-Si	kg	1.58	polycrystalline silicon of semiconductor or solar grade quality, partly internally recycled silicon from ingot cut-offs and broken wafers
quartz crucible	kg	0.36	for ingot growing
glass	kg	0.01	for temporarily attachment of bricks to wiresawing equipment, assumed same as multi wafers
steel wire	kg	1.49	for wafer cutting, assumed same as multi wafers
silicon carbide (SiC)	kg	2.61	for sawing slurry, assumed same as multi wafers
GASES			
argon (Ar)	kg	6.20	for ingot growing
LIQUIDS			
polyethylene glycol (PEG)	kg	2.63	for sawing slurry, assumed same as multi wafers
dipropylene glycol monomethyl ether (DPM)	kg	0.30	for sawing slurry, assumed same as multi wafers
adhesive	kg	0.002	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	0.24	for wafer cleaning
Sodium hydroxide, 50% in H_2O	kg	0.015	see note 1, for wafer cleaning, assumed same as multi wafers
Hydrochloric acid, 30% in H_2O	kg	0.0027	see note 1, for wafer cleaning, assumed same as multi wafers
Acetic acid, 98% in H_2O	kg	0.039	see note 1, for wafer cleaning, assumed same as multi wafers
tap water	kg	0.006	for ingot sawing
water, deionised	kg	65	for wafer cleaning
Electricity/fuel			
electricity, medium voltage	kWh	145	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	77	general use + furnaces
Final waste flows			
Silicon waste (not recycled)	kg	0.4	unused part of ingot, estimate
Waste to treatment			
cutting waste (Si + slurry)	kg	6.0	not recycled internally, but SiC and cutting fluids may be partially recovered at specialized facility

Table III. Life Cycle Inventory data for the production of multicrystalline silicon wafers from polycrystalline silicon

Name	**multi-silicon wafer from poly-Si**
Time period	2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 3 companies, total production 1.5E6 m2 wafer area.
Collection method	Data collection by factory representatives.
Data treatment	
Comment	Includes both the ingot growth and wafer cutting processes. Average wafer thickness 285 um. The process for internal recycling of silicon is NOT included in the process data, external recyling of sawing slurry is not accounted either. The amount of poly-silicon includes virgin AND recycled silicon.

Products	**Unit**	**Amount**	**Comment**
multi-Si wafer	m^2	1.0E+00	typical wafer area: 125x125 mm^2 (0.0156 m^2), average thickness 285 um
Materials			
SOLIDS			
poly-Si	kg	1.67E+00	polycrystalline silicon of semiconductor or solar grade quality, partly internally recycled silicon from ingot cut-offs and broken wafers
quartz crucible	kg	3.90E-01	for ingot growing
glass	kg	1.00E-02	for temporarily attachment of bricks to wiresawing equipment
steel wire	kg	1.49E+00	for wafer cutting
silicon carbide (SiC)	kg	2.61E+00	for sawing slurry
GASES			
nitrogen (N_2)	kg	5.33E-02	for ingot growing
argon (Ar)	kg	3.04E-01	for ingot growing
helium (He)	kg	1.36E-04	for ingot growing
LIQUIDS			
polyethylene glycol (PEG)	kg	2.63E+00	for sawing slurry
dipropylene glycol monomethyl ether (DPM)	kg	3.03E-01	for wafer cleaning
adhesive	kg	2.00E-03	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	2.37E-01	for wafer cleaning
Sodium hydroxide, 50% in H_2O	kg	1.49E-02	see note 1, for wafer cleaning
Hydrochloric acid, 30% in H_2O	kg	2.72E-03	see note 1, for wafer cleaning
Acetic acid, 98% in H_2O	kg	3.90E-02	see note 1, for wafer cleaning
tap water	kg	6.41E-03	for ingot sawing
water, deionised	kg	6.49E+01	for wafer cleaning

Electricity/fuel			
electricity, medium voltage	kWh	3.00E+01	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	3.96E+00	for removing adhesive after sawing
Final waste flows			
silicon waste (not recycled)	kg	3.00E-01	unused part from ingot, estimate
Waste to treatment			
cutting waste (Si + slurry)	kg	6.2E+00	not recycled internally, but SiC and cutting fluids may be partially recovered at specialized facility

Table IV. Life Cycle Inventory data for the production of multicrystalline silicon ribbons from polycrystalline silicon

Name	**ribbon silicon wafer from poly-Si**
Time period	2004
Geography	Europe, Western + North America
Technology	Average technology
Representativeness	Average from 3 specific processes of which one in pilot phase.
Collection method	Data collection by factory representatives.
Data treatment	
Comment	Wafer thickness 300-330 um. Wafer area 120-156 cm^2.

Products	**Unit**	**Amount**	**Comment**
ribbon Si wafer	m^2	1	
Materials/fuels			
SOLIDS			
poly-Si	kg	0.91	
graphite	kg	0.014	
GASES			
argon (Ar)	kg	4.38	
Electricity			
electricity, medium voltage, total	kWh	45.7	
Emissions to air			
argon	kg	4.38	
Waste to treatment			
graphite crucibles	kg	0.014	
wafer waste, to recycling	kg	0.09	

Table V. Life Cycle Inventory data for the production of crystalline silicon solar cells from wafers

Name	**multi- or mono-crystalline silicon cell**
Time period	2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 5 specific processes and companies (4 multi + 1 mono)
Collection method	Data collection by factory representatives.
Data treatment	Some inputs and emissions aggregated to protect sensitive data.
Comment	Wafer thickness 270-300 um.

Products	**Unit**	**Amount**	**Comment**
multi- or mono-Si cell (156 cm^2)	p	1.00	cell area 156 cm^2, typical thickness 270-300 um
Resources			
Water, cooling	m^3	1.56E-02	cooling water
Materials/fuels			
SOLIDS			
multi/mono-Si wafer (156 cm^2)	p	1.06E+00	
phosphorus paste	kg	2.27E-05	for emitter formation
metallisation paste	kg	1.17E-03	aggregated value for front and back pastes containing, silver content 1.6E-4 kg
polystyrene, expandable	kg	6.36E-06	for packaging
GASES			
nitrogen (N_2)	kg	2.89E-02	
oxygen (O_2)	kg	1.59E-03	
argon (Ar)	kg	4.01E-04	
Fluorinated compound mix (CF_4, C_2F_6, SF_6, NF_3)	kg	4.93E-05	aggegrate value for different fluorinated source gases
ammoniak (NH_3)	kg	1.05E-04	for silicon nitride deposition
silane (SiH_4)	kg	1.89E-05	for silicon nitride deposition
LIQUIDS			
sodium hydroxide, 50% in H_2O (NaOH)	kg	2.45E-03	
acetic acid, 98% in H_2O (CH_3COOH)	kg	4.42E-05	
hydrochloric acid, 30% in H_2O (HCl)	kg	7.12E-04	
hydrogen fluoride (HF) 100%	kg	5.89E-04	
nitric acid, 50% in H_2O (HNO_3)	kg	4.17E-04	
$POCl_3$ phosphoryl chloride	kg	3.39E-06	for emitter formation
phosphoric acid, industrial grade, 85% in H_2O (H_3PO_4)	kg	1.19E-04	for emitter formation

sodium silicate	kg	1.17E-03	
calcium chloride ($CaCl_2$)	kg	3.37E-04	
tetraisopropyltitanate (TPT, a titanium precursor)	liter	2.22E-08	for titanium dioxide antireflection coating deposition
isopropanol	kg	1.23E-03	
ethanol	kg	9.98E-06	
solvents, organic, unspecified	kg	2.24E-05	
water, deionised	kg	2.15E+00	
Electricity			
electricity, medium voltage	kWh	5.90E-01	
natural gas	MJ	7.42E-02	
fuel oil	liter	5.06E-04	
Emissions to air			
aluminum	kg	1.21E-05	
hydrogen chloride	kg	4.16E-06	
hydrogen fluoride	kg	7.56E-08	
lead	kg	1.21E-05	
particulates, unspecified	kg	4.16E-05	
silicon dioxide	kg	1.13E-06	
silver	kg	1.21E-05	
sodium hydroxide	kg	7.56E-07	
tin	kg	1.21E-05	
VOC, volatile organic compounds	kg	3.02E-03	
FC-gases (CF_4, C_2F_6, SF_6, NF_3)	kg CO_2-eq	4.41E-02	Emission in **kg CO_2 equivalent**, estimate based on 70% source gas utilisation
Final waste flows			
Photovoltaic cell waste	kg	4.31E-03	
Waste to treatment			
multi-Si cell, to recycling	p	1.76E-02	
neutral solution	m^3	7.31E-01	
alkaline solution	m^3	2.17E-04	
acid solution	m^3	7.87E-04	
organic waste	liter	1.22E-04	

Table VI. Life Cycle Inventory data for the production of crystalline silicon modules from solar cells

Name	**Crystalline silicon PV module production**
Time period	2004
Geography	Europe, Western
Technology	Mixed data

Representativeness	Average from 2 companies + literature data
Collection method	Data collection by factory representatives and literature data.
Data treatment	
Comment	Only materials and energy use for module lamination and further assembly. Typical total area (excluding frame) efficiencies are 14.0% for mono-Si modules, 13.2% for multi-Si modules and 11.2% for ribbon-Si modules.

N.B.: Module parameters may be changed below (red figures):

Number of cells, width:	**6**	
Number of cells, length:	**12**	
Cell size (length):	**12.5**	cm
Cell area factor:	**1.00**	
Cell efficiency (encapsulated)	**14.7**	%

Calculated parameters:

Module width (w/o frame)	**80**	cm
Module lenght (w/o frame)	**156**	cm
Module area (w/o frame)	**1.25**	m^2
Module perimeter (=frame length)	**4.72**	m
Number of cells:	**72**	
Module power	**165**	Wp
Module efficiency (glass area, excl. frame)	**13.2**	%

N.B.: Material quantities below are calculated from the module parameters above

Products	**Unit**	**Amount**	**Comment**
Module, c-Si	pc	1.00	dimensions see above
Materials			
Solar cells	pc	73.4	+2% cell loss
Aluminium profile	kg	3.8	for frame, may vary per manufacturer
Polyphenylenoxid	kg	0.2	junction box, may vary per manufacturer
Glass sheet, low iron, tempered	kg	11.4	assuming 3.6 mm glass thickness, varies from 3.2 to 4.0 depending on application, size and manufacturer, +1% loss
Ethyl Vinyl Acetate	kg	1.3	EVA consumption 0.96 kg/m^2, +6% more than glass area
Back foil, for solar cell module	kg	0.32	50% polyvinylfluoride, 50% polyethylene terephthalate, 0.243 g/m^2 (0.17 mm thickness) 7% cutting loss
Copper	kg	0.14	copper ribbbons for cell interconnection
Tin	kg	0.007	Sn60Pb40 plating on tabbing material, Sn plating on interconnect/terminal ribbons
Lead	kg	0.004	Sn60Pb40 plating on tabbing material, some manufacturers use lead free.
Nickel	kg	0.00020	Ni plating on interconnect/terminal ribbons
Soldering flux	kg	0.0100	soldering flux, 95% propanol, no halogens
Methanol	kg	0.0162	cleaning fluid 13 ml/m^2

Silicone	kg	0.0029	for diaphragma of laminator
Silicone kit	kg	0.150	kit to attach frame and junction box
Cardboard	kg	1.37	packaging; estimation: 2 modules per cardboard box, 1 kg/m^2 board, 2.2 m^2 board per m^2 module
Tap water	kg	27	for glass rinsing and general use
Electricity			
Electricity, medium voltage	kWh	**8.33**	total process energy
Final waste flows			
Solar cells waste	kg	0.015	2% loss, 10 g per cell, may be recycled
Waste to treatment			
Solar glass, low-iron, to recycling	kg	0.11	1% breakage loss assumed
Ethylvinylacetate, foil, to waste incineration	kg	0.05	4% cutting loss
Back foil, to waste incineration	kg	0.02	7% cutting loss