Part XII

Photovoltaics

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Abstract

Solar radiation is a source for renewable energy. One possible use is the production of electricity in photovoltaic appliances (PV). The aim of this report is to provide up-to-date data for the environmental impacts of electricity production with photovoltaic appliances in Switzerland and Europe. The data for photovoltaics have been updated with financial contribution of the European Photovoltaics Industry Association and the Swiss Federal Office of Energy.

Data have been collected in this project directly from manufacturers and were provided by other research projects. Life cycle assessment (LCA) studies from different authors are considered for the assessment. The information is used to elaborate a life cycle inventory from cradle to grave for the PV-electricity production in 3kWp plants in the year 2005 (kW_p - kilowatt peak). The inventory is investigated for single- and multicrystalline cells, ribbon-silicon, amorphous-silicon, CdTe and CIS thin film cells. Environmental impacts i.e. due to the infrastructure for all production stages are also considered in the inventory.

Preface for the update in the frame of ecoinvent data v2.1

Within the update in the frame of ecoinvent data v2.1, changes mainly in two fields were adopted; the CdTe photovoltaic datasets and the mounting structures were updated.

Since the CdTe modules are only produced without framing materials, the corresponding datasets ar newly referred to as CdTe laminates instead of CdTe panels as before. In addition, the CdTe laminate producer and the market shares of different production sites were updated. Furthermore, the Cadmium emission factor in semiconductor grade Cadmium production was adjusted (reduced by a factor of about 20).

The average weight of different mounting systems was calculated with data from the latest market survey (Siemer 2008), wheras each product on the market was weighted by its installed capacity in Europe. From the updated weight figures, correction factor were identified in order to ajust old data on material quantities to the current market situation.

Preface for the update in the frame of ecoinvent data v2.0

In the past years the PV sector developed rapidly. Ongoing projects such as *CrystalClear*[1] have investigated the up-to-date life cycle inventory data of the multi- and singlecrystalline technologies (de Wild-Scholten & Alsema 2005). Updated LCI data of single- and multicrystalline PV technologies were investigated within the framework of the CrystalClear project based on questionnaires sent to different involved industries. The data investigated with 11 European and US photovoltaic companies for the reference year 2005 are now implemented in the ecoinvent database and documented according to the ecoinvent requirements. The following unit process raw data are investigated and updated:

- multicrystalline SoG-silicon, Siemens process (new solar-grade process)
- multicrystalline-Si wafer (mc-Si or multi-Si)
- singlecrystalline-Si wafer (sc-Si or single-Si)
- ribbon Si wafer (so far not covered by ecoinvent data v1.3)
- ribbon-, multi- or single-Si cell (156 mm x156 mm)
- modules, ribbon-Si (new) and other module types
- silica carbide (SiC)

[1] See www.ipcrystalclear.info for detailed information.

- PV-electricity mix Switzerland and in other countries
- recycling of sawing slurry and provision of SiC and glycol
- front metallization paste and back side metallization paste of solar cells
- inverter including electronic components[2]

The naming convention for crystalline cells has been updated according to the today usage. Instead of monocrystalline cells we speak now of singlecrystalline silicon (sc-Si) cells. Instead of polycrystalline we use multicrystalline silicon (mc-Si).

New technologies like thin film cells like CIS or CdTe are entering the market. For the first time also thin film photovoltaics (CIS, CdTe and amorphous silicon) are investigated for the ecoinvent data based on literature information.

The yield per kW_p is one important factor for the comparison of PV with other types of electricity production. For ecoinvent data v1.3 only the situation in Switzerland has been investigated. Now we investigate the electricity mixes for several European countries with the specific yields for each country. Also non-European countries (e.g. from Asia, Australia and North-America) are considered for this calculation. It should be noted that different electricity/energy mixes for the manufacturing upstream chain have not been modelled in any case. The extrapolation to non-European countries has been made basically only using specific average country-wide electricity yields at the power plant.

So far not many experiences exist concerning the end-of-life treatment of PV plants. The modelling is based on today expectations and not on real experiences.

The whole report has been translated to English in order to facilitate the discussion about the PV life cycle inventory data e.g. within the framework of planed IEA-PVPS activities.

Acknowledgements ecoinvent v2.0

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Vorwort zur Überarbeitung im Rahmen von ecoinvent Daten v1.0

Die der Ökobilanz von schweizerischen Photovoltaikanlagen bisher zugrandeliegenden Sachbilanzda-

[2] This part of the report has been elaborated by M. Tuchschmid, ESU-services Ltd.

ten aus den „Ökoinventaren von Energiesystemen“ von 1996 basierten auf deutschen Studien die im Jahr 1992 veröffentlicht wurden. Sie sind damit 10 Jahre alt. Die Photovoltaik ist einem raschen Wandel unterworfen. Eine gründliche Neubearbeitung war deshalb notwendig (Jungbluth 2003; Jungbluth et al. 2004; Jungbluth 2005).

Grundlage für diese Überarbeitung ist die Studie von Jungbluth & Frischknecht (2000) in der die Daten der vorhergehenden Auflage kritisch überprüft und dort wo notwendig an neue Entwicklungen angepasst wurden. Dabei wurde ein optimierter Produktionsweg angenommen. Für die *ecoinvent* Datenbank wird nun eine Durchschnittsbetrachtung für die Produktion im Jahr 2000 erarbeitet and ein Szenario für zukünftige Entwicklungen abgeschätzt. Dafür wurde eine Reihe weiterer Literaturquellen und neue Herstellerangaben ausgewertet.

Grundlage für den Text dieser Überarbeitung ist das entsprechende Kapitel aus den „Ökoinventaren von Energiesystemen“. Literatur, die bereits in dieser Studie zitiert wurde wird in eckige Klammern <xxx> gesetzt. Die neu zitierte Literatur wird in runden Klammern (xxx) gezeigt. Am Schluss des Berichtes befinden sich hierfür zwei getrennte Literaturverzeichnisse.

Verdankungen zur Aufdatierung für ecoinvent Daten v1.0

Für das Update der Sachbilanzdaten, haben uns eine Reihe von Autoren ihr Material and weitere Hintergrandinformationen zu ihren Studien zur Verfügung gestellt. Wir möchten hiermit Erik Alsema, Vasilis Fthenakis, J.R. Bohland, Marion Engeler, Hans Uwe Florstedt, Paolo Frankl, James M. Gee, Stephan Gnos, Dirk Gürzenich, Dirk Hartmann, Karl E. Knapp, Wolfgang Koch, Volker Lenz, A. Loipführer, Rick Mitchell, Martin Pehnt, Bent Sørensen, Eric Williams and Ken Zweibel für ihre Hilfestellung danken. Bedanken möchten wir uns ausserdem bei verschiedenen MitarbeiterInnen der Firmen Gebäude-Solarsysteme GmbH, Löbichau, Solon AG, Berlin and Wacker Silitronic AG, Werk Freiberg für ihre mündlich and schriftlich erteilten Auskünfte.

Verdankungen 1994-1996

In dieser Arbeit waren wir sehr darauf angewiesen, Informationen von Produzenten photovoltaischer Komponenten and von Anlagenbauern zu sammeln. Wir danken an dieser Stelle folgenden Personen, die bereitwillig Auskunft gaben:

G. Hagedorn, Siemens AG, Erlangen; ehemals Forschungsstelle für Energiewirtschaft (FfE), München, Y. Tsuji, Kyocera Corp., Kyoto, Japan, M. G. Real, R. Moser, Alpha Real Ingenieurunternehmungen, Zurich, R. Hächler, Ars *solar*is, Chur, Herrn Von Bergen, Ingenieurschule Biel, Hermann Damann, ARBA Strom, Winterthur.

Zusammenfassung

Ziel der erstellten Sachbilanzen ist die Erfassung der Stoff- and Energieströme für die Produktion von Elektrizität mit netzgebundenen Photovoltaikanlagen in der Schweiz und in vielen weiteren Ländern. Für die Aufdatierung der Ökobilanz wurden alle Prozessschritte von der Silizium Produktion bis zum Betrieb der Anlagen mit den zur Verfügung stehenden aktuellen Informationen überarbeitet. Dabei wird die Marktsituation im Jahr 2005 abgebildet. Einen Überblick zu den wichtigsten Annahmen und Änderungen gibt Tab. 14.3.

Für die MG-Silizium Produktion haben sich im Vergleich zur letzten Auflage nur geringe Änderungen bei der Bilanz ergeben.

Die Herstellung von gereinigtem Silizium (Halbleiterqualität oder solar-grade Silizium aus modifiziertem Siemensverfahren), CZ-sc-Silizium (Einkristall Silizium aus dem Czochralski-Tiegelziehverfahren), das Blockgiessen und die Waferfertigung wird in getrennten Teilschritten bilanziert. Für die Bereitstellung von gereinigtem Silicon werden die Marktverhältnisse im Jahr 2005 be-

trachtet. Dafür wurden für die Herstellung von SoG-Si (*solar*-grade) aktuelle Daten erhoben.

Für die Waferfertigung wird von einer teilweisen Recyclingmöglichkeit für Sägeabfälle ausgegangen. Berücksichtigt werden detailliertere Angaben zum Wasserverbrauch und zur Emission von Wasserschadstoffen bei der Waferfertigung. Erstmals wurden dabei auch Daten zu amorphem Silizium erhoben.

Für die *Solarzellen* Fertigung (und alle anderen Produktionsschritte) wird auch die Infrastruktur mit berücksichtigt. Neu werden in dieser Studie auch sogenannte Dünnschichtzellen bilanziert. Dabei werden sowohl CdTe als auch CIS Zellen betrachtet. Erstmals wird eine Bilanz für ribbon-Silizium Zellen erstellt. Dabei wird der multikristalline Silizium Wafer direkt aus der flüssigen Siliziumschmelze gezogen und so eine höhere Materialeffizienz erreicht. Alle sechs Typen von Solarzellen werden separat bilanziert. Durch die separate Bilanzierung der Zellen kann eine beliebige Kleinanlage aus den Grundlagendaten kombiniert werden.

In diesem Projekt werden die Paneel- und die Laminat-Bauweise bilanziert. Die Paneels haben eine eigene tragende Struktur und können an der Gebäudehülle aufgesetzt werden; Laminat-Konstruktionen müssen in das Gebäude integriert sein. In der Bilanz der Panelfertigung werden aktuelle Daten zur Effizienz von *Solarzellen* verwendet.

Im Bereich der Stromproduktion ab Photovoltaikanlage werden verschiedene gebäudeintegrierte Kleinanlagen (3 kW_p) bilanziert. Modular aufgebaute Anlagen der mittleren Leistungsklasse können als Vielfaches der 3 kW_p-Kleinanlage berechnet werden.

Für den Anlagenbetrieb wurden aktuelle Daten (Zeitreihen) zum Stromertrag von Schweizerischen Photovoltaikanlagen ausgewertet. Dabei wird ein durchschnittlicher Standort in der Schweiz mit einem Jahresertrag von 820 kWh pro Jahr und installiertem kW-Peak (kW_p) zugrundegelegt. Für alle Schräg- und Flachdachanlagen wird ein Wert von 920kWh/kW_p. verwendet Der berechnete Ertrag für Fassadenanlagen liegt bei 620 kWh/kW_p. Eine Durchschnittsbilanz für die Stromerzeugung mit PV Anlagen wird auch für eine Reihe weiterer Länder auf Grundlage veröffentlichter Ertragszahlen erstellt.

Die Resultate für die Bilanz einer gesamten Photovoltaik-Anlage zeigen, dass der Hauptteil des Ressourcenverbrauchs und viele Emissionen aus dem Stromverbrauch für die Fertigung der Solarzellen und der Paneels stammt. Damit kommt dem Standort der Produktionsanlagen eine besondere Bedeutung zu. Die Analyse zeigt auch, dass relevante Umweltbelastungen in allen Stufen der Produktion anfallen. Aufgrund der inzwischen verbesserten Produktion für Solarzellen, steigt die Bedeutung der übrigen Komponenten einer PV-Anlage weiter an. Zu diesen Komponenten gehört das Befestigungssystem, der Wechselrichter und die elektrische Installation. Insbesondere bei Solarzellen mit geringer Effizienz kommt dem Befestigungssystem inzwischen eine relevante Bedeutung zu.

Eine Reihe von Schadstoffen wird dabei unabhängig vom Energieverbrauch emittiert. Eine Energiebilanz alleine reicht somit zur Beurteilung dieses Energiesystems und zum Vergleich mit anderen Systemen nicht aus.

Für alle relevanten Produktionsschritte konnten die bisherigen Daten aktualisiert und ergänzt werden. Die Bilanzen wurden teilweise aus Einzelbetrachtungen verschiedener Hersteller kombiniert. Im Vergleich zu den ersten Schweizer Ökobilanzen für Photovoltaik ist der kumulierte Energiebedarf pro Stromertrag um den Faktor 3 zurückgegangen.

Auf Grund des raschen technologischen Fortschritts in der Produktion von PV-Anlagen stellt auch diese Ökobilanz keinen Endpunkt in der Betrachtung dar. Vielmehr ist eine Aufdatierung nach einiger Zeit wünschenswert. Hierfür wären insbesondere vollständige und aktuelle Angaben von Herstellern aus verschiedenen Stufen des Produktionszyklus sehr erwünscht.

Die aktualisierten und ergänzten Sachbilanzdaten können als Grundlage für die ökologische Beurteilung von Photovoltaikanlagen in der Schweiz und in vielen weiteren Ländern herangezogen werden. Die hier erhobenen Ökobilanzdaten ermöglichen auch den Vergleich der Umweltbelastungen mit anderen Technologien für die Bereitstellung von Elektrizität. Zu beachten ist dabei aber, dass für andere

Elektrizitätssysteme die Herstellung der notwendigen Infrastruktur evtl. nicht in ähnlich grosser Detailtiefe wie für Photovoltaikanlagen erfolgte.

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1 Introduction

1.1 Background of this study

LCA studies for photovoltaic power plants have a long tradition of more than 20 years (e.g. Alsema 2000a; Dones & Frischknecht 1998; Frankl 1998; Frischknecht et al. 1996; Fthenakis et al. 1999; Hagedorn & Hellriegel 1992; Jungbluth & Frischknecht 2000; Jungbluth et al. 2004; Jungbluth 2005; Kato 1999; Knapp & Jester 2000a; Meijer et al. 2003; Palz & Zibetta 1991; Pehnt et al. 2002; Phylipsen & Alsema 1995; Tsuo et al. 1998). The published studies show a high variation in results and conclusions. This is partly due to the rapid development in this industrial sector, which leads to constant improvements in all parts of the production chain.

The cumulative energy demand, for example, has been investigated by different authors ranging from 3410 to 13'400 MJ-eq per square metre of a multicrystalline panel. The main reasons for the different LCA results have been evaluated in the late nineties (Alsema et al. 1998; Dones 2000; Jungbluth & Frischknecht 2000). Critical issues during modelling of a life cycle inventory (LCI) for photovoltaics are: modelling of silicon inputs and use of off-grade or solar-grade silicon, allocation between different silicon qualities in the silicon purification process, power mixes assumed for the production processes, and process specific emissions. The production technology for photovoltaic power plants has constantly been improved over the last decades, e.g. for the efficiency of cells, the required amount of silicon, and the capacity of production processes. The availability of data is a major problem for establishing a high quality inventory.

In the past years the PV sector developed rapidly. Ongoing projects such as *CrystalClear* have investigated the up-to-date life cycle inventory data of the multi- and singlecrystalline technologies (de Wild-Scholten & Alsema 2005). These data are based on questionnaires sent to different involved industries. Several producers have now provided reliable and verifiable data. The investigated data from 11 European and US photovoltaic companies for the reference year 2005 is implemented with this report in the ecoinvent database and documented according to the ecoinvent requirements (Frischknecht et al. 2007a).

Since the last update of this study in 2003, the market of photovoltaic systems has grown by a factor of two. New technologies like thin film cells in CIS or CdTe are entering the market. For the first time also thin film photovoltaics are investigated for the ecoinvent data based on literature information. In this report, as far as possible, we used the most recent information for modelling the life cycle inventories of photovoltaics production technologies. Older data are just shown for informative purposes.

1.2 Technologies

Different solar cells are on the market and new technologies are investigated. Until now, the most dominant basic material is silicon. It is one of the most common elements on earth. Different types of technologies can be distinguished for silicon based solar cells.

- *Singlecrystalline silicon cells (*sc-Si*) (or monocrystalline):* The active material is made from a single crystal without grain boundaries. The sc-Si-*cells* have the highest efficiencies (for commercial *cells* between 13-18%).
- *Multicrystalline*[3] *silicon cells (*mc-Si*):* The cell material consists of different crystals with different orientation. The domain boundaries or grain boundaries lead to electron-hole-recombination losses. Thus, this type of cells has a lower efficiency, but it is cheaper in production. Commercial mc-Si-cells have an efficiency of about 11-16%.
- *Ribbon silicon (ribbon*-Si). Ribbon technologies use the available silicon more efficiently. The

[3] In the last version of this report, this type of cells has been labelled as polycrystalline.

wafers are directly crystallized from the silicon melt. Thus no sawing losses occur. Ribbon cells have an efficiency of about 10-12%.

- *Thin films.* Thin film modules are constructed by depositing extremely thin layers of photovoltaic materials on a low cost backing such as glass, stainless steel or plastic. Individual 'cells' are formed by then scribing through the layers with a laser. Thin film cells offer the potential for cost reductions. Firstly, material costs are lower because much less semiconductor material is required and, secondly, labour costs are reduced because the films are produced as large, complete modules and not as individual cells that have to be mounted in frames and wired together. The types of thin films investigated in this study are cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS).
- *Amorphous cells (a-Si):* A fully developed thin film technology is hydrogenated amorphous silicon. The active material is an unstructured glass-type mixture of silicon and hydrogen. The efficiency of amorphous cells decreases in the first hundred operation hours (so called Staebler-Wronski-effect). The final efficiency is about 7-9% while shortly after production the cell has efficiencies between 9% and 11%.

1.3 History

Photovoltaics have a short history – compared to conventional sources of electricity. Edmund Becquerel has first described the so-called photovoltaic effect in 1839 for the semi-conductor silicon. Until the nineteen thirties it was only known by experts. The first solar cell made from silicon has been produced in 1954 and first been used in 1958. The early stages of development are listed below.

- 1839: Discovery of the photovoltaic effect with silicon by E. Becquerel
- 1923: Albert Einstein gets the Nobel-price for his theories dealing with the photovoltaic effect
- 1954: Singlecrystalline silicon solar cells (sc-Si) by Pearson, Chapin and Fuller (Bell Laboratories) have an efficiency of 6%
- 1956: First solar cell made with gallium arsenide (GaAs)
- 1958: NASA-satellite „Vanguard“ with sc-Si-solar cells with less than 1 kilowatt capacity in space
- 1962: sc-Si-solar radio
- 1972: Silicon-solar cell made with multicrystalline wafer material (mc-Si).
- 1976: Silicon-solar cell made with amorphous silicon (a-Si)
- 1978: sc-Si-operated pocket calculator
- 1979: a-Si- operated pocket calculator
- 1981: 350 kW_p-plant (kilowatt peak) Soleras/Hysolar for hydrogen production in Riad, Saudi Arabia
- 1983: 6400 kW_p-plant Carissa Plains in California, US
- 1984: First race for solar mobiles (Tour de Sol) in Switzerland
- 1986. First large plant with amorphous cells, 75 kW_p in Birmingham, Alabama
- 1988: Cell efficiencies of more than 30% in laboratory conditions (GaAs / sc-Si - cell)
- 1989: 219 grid-connected plants in the USA have a capacity of 11 Megawatt
- 1989: First large plant in Switzerland with 100 kW_p at the national route No. 13, Domat/Ems GR
- 1990: Trans continental flight of a solar run air plane over the USA
- 1992: Swiss plant with 500 kW_p on Mont Soleil (PHALK 500)
- 2000: In Berne a 2000m^2 photovoltaic plant with 200kW_p is installed.

- 2001: Construction of a 3.3MWp plant in Serro, IT.
- 2001: An unmanned solar air plane reaches the record height of 29'000 metres
- 2001: Operation of a solar boat on lake Zurich[4]
- 2002: Solar park “Sonnen” in Germany with 1.8MWp capacity on open space
- 2002: World biggest roof-integrated plant with 2.3MWp for the „Floriade“ in the Netherlands
- 2003: Solar park Hernau, Germany with 4MWp capacity
- 2005: With 1537 kWh/kWp delivered the alpine photovoltaic-plant on the Jungfraujoch a new top result
- until 2007 much larger plants were erected in different countries

1.4 Characterisation of photovoltaics

The different advantages and disadvantages of photovoltaics can be summarized as follows (<Kuwano 1992> and own additions).

Major advantages of photovoltaics

- Solar energy is fully non-exploitable, because it is renewable. The total solar irradiation of the sun to the earth surface is about $1.8 \cdot 10^{14}$ kW which is $5.6 \cdot 10^{12}$ TJ per year.
- The conversion of solar energy has no emissions during operation. There are no moving part which might cause noise. Only optical disturbance is possible.
- Photovoltaics are flexible in terms of possible uses. The applications reach from single milliwatts, e.g. in clocks, to large plants with several megawatts. There is no other system of electricity generation that allows applications in such many orders of magnitude.
- Photovoltaic cells can be combined modular to different capacities. Thus they can be used quite easily for decentralized energy production.
- Also diffuse light and light indoors can be transformed to electricity.

Further advantages of photovoltaics

- Silicon is the second most abundant element on earth.
- Silicon is not toxic.
- Integration in buildings is possible

Major disadvantages of photovoltaics

- The convertible energy density is low.
- Electricity production depends on weather conditions and irradiation. Electricity production is only possible if light is available. There is no good storage facility developed yet.

Further disadvantages of photovoltaics

- Silicon has to be purified in an energy intensive process and is thus expensive.
- New types of solar cells might need rare elements for production.

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[4] http://www.solarboats.net/pages/constr/zuriboot.html

- The production needs specific technologies and highly purified input materials. Thus a global production chain has been developed with a separation between the different production stages. The whole production chain cannot be found ata local scale.
- Large land areas are necessary if photovoltaic plants are installed on open-ground.

1.5 Future developments

Silicon for solar cells needs a high purification grade. The purification and the necessary production plants are a major economic factor and they are responsible for a large part of the energy consumption. Thus the major improvement strategies are:

- Reduction of the silicon consumption per kW_p by thinner wafers, less kerf losses, recycling of silicon.
- Improvement of the cell efficiencies.
- Development of purification technologies specific for photovoltaic use (solar Grade Silicon - SoG).

Steadily new types of technologies are introduced to the market. Nowadays new types of semiconductor materials are used for solar thin film cells. The most important are copper-indium-diselenide ($CuInSe_2$ or short CIS) and cadmium-telluride (CdTe), which are investigated in this study. Others are indium-phosphid (InP), dye-sensitized with titanium dioxide (TiO_2) and gallium-arsenide (GaAs).

2 Today use and production of photovoltaic

2.1 Worldwide PV production

2.1.1 Potential electricity production

A study of the IEA-PVPS has investigated the potential of BIPV (building integrated photovoltaics) for several countries (IEA-PVPS 2002). Tab. 2.1 shows the potential and a comparison with the actual electricity consumption in 1998.

Tab. 2.1 Solar electricity BIPV potential fulfilling the good solar yield (80% of the maximum local annual solar input, separately defined for slope roofs and façades and individually for each location / geographical unit), (IEA-PVPS 2002)

Solar electricity BIPV production potential	Potential production of solar electricity (TWh/y) on roofs	Potential production of solar electricity (TWh/y) on façades	Potential productio of solar electricity (TWh/y) on buildin envelope	Actual electricity consumption (in TWh)	Ratio "solar electri production potenti electricity consumption"
Australia	68.176	15.881	84.057	182.24	46.1%
Austria	15.197	3.528	18.725	53.93	34.7%
Canada	118.708	33.054	151.762	495.31	30.6%
Denmark	8.710	2.155	10.865	34.43	31.6%
Finland	11.763	3.063	14.827	76.51	19.4%
Germany	128.296	31.745	160.040	531.64	30.1%
Italy	103.077	23.827	126.904	282.01	45.0%
Japan	117.416	29.456	146.872	1 012.94	14.5%
Netherlands	25.677	6.210	31.887	99.06	32.2%
Spain	70.689	15.784	86.473	180.17	48.0%
Sweden	21.177	5.515	26.692	137.12	19.5%
Switzerland	15.044	3.367	18.410	53.17	34.6%
United Kingdom	83.235	22.160	105.395	343.58	30.7%
United States	1 662.349	418.312	2 080.661	3 602.63	57.8%

2.1.2 Installed capacity until 2005

During the last years the global electricity production of photovoltaic plants has been increased considerably. The worldwide production in 2005 was 1740 MWp and thus about 40% more than in the year before. Japan is the largest producer of solar cells followed by Germany, USA and China (IEA-PVPS 2006; Jäger-Waldau 2006).

The installed capacity has been increasing rapidly. Since the first version of this report in 1994, the installed capacity has increased by more than a factor ten. More than 3500 MWp were installed in the year 2005 (IEA-PVPS 2006).

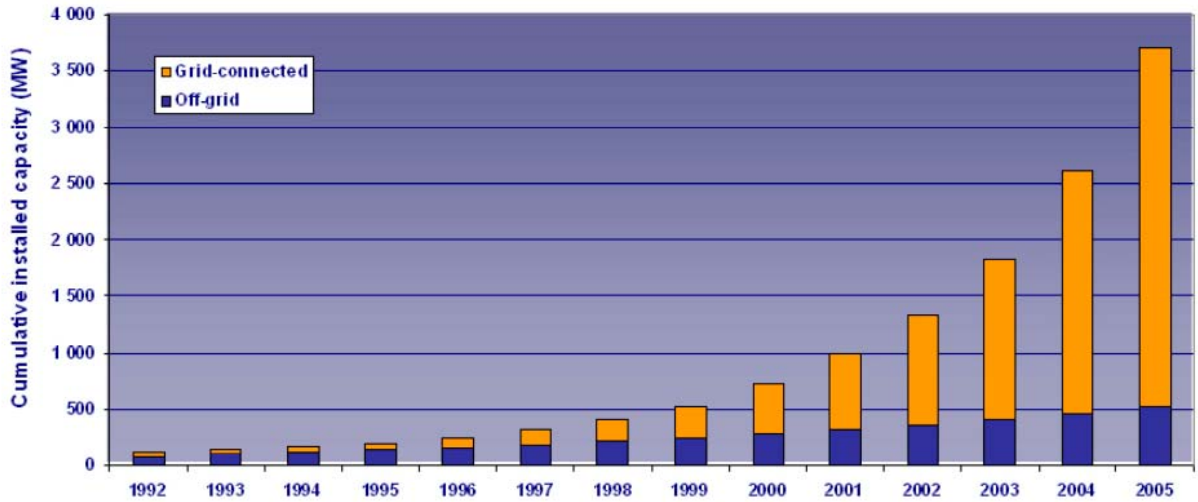

Fig. 2.1 **Cumulative installed grid-connected and off-grid PV power in the IEA PVPS reporting countries (IEA-PVPS 2006)**

Tab. 2.2 shows the different types of applications in different countries and a comparison of the installed capacity per capita.

Tab. 2.2 **Installed PV power in reporting IEA PVPS countries as of the end of 2005 (IEA-PVPS 2006[5])**

Country	Cumulative off-grid PV capacity [kW]		Cumulative grid-connected PV capacity [kW]		Total installed PV power [kW]	Total installed per capita [W/Capita]	PV power installed in 2005 [kW]	Grid-connected PV power installed in 2005 [kW]
	Domestic	Non-domestic	Distributed	Centralized				
AU	8'768	33'073	6'860	1'880	**60'581**	2.97	8'280	1'980
AT	2'895		19'973	1'153	**24'021**	2.93	2'961	2'711
CA	5'903	9'719	1'059	65	**16'746**	0.52	2'862	612
CH	2'930	320	21'240	2'560	**27'050**	3.66	3'950	3'800
DE	29'000		1'400'000		**1'429'000**	17.32	635'000	632'000
DK	70	225	2'355	0	**2'650**	0.49	360	320
ES	15'800		41'600		**57'400**	1.32	20'400	18'600
FR	13'844	6'232	12'967	0	**33'043**	0.54	7'020	5'900
UK	227	697	9'953	0	**10'877**	0.18	2'732	2'567
IL	809	210	11	14	**1'044**	0.15	158	2
IT	5'300	7'000	8'500	6'700	**37'500**	0.64	6'800	6'500
JP	1'148	85'909	1'331'951	2'900	**1'421'908**	11.13	289'917	287'105
KR	853	4'810	8'028	1'330	**15'021**	0.31	6'487	6'183
MX	14'476	4'178	40	0	**18'694**	0.17	513	30
NL	4'919		43'377	2'480	**50'776**	3.12	1'697	1'547
NO	6'800	377	75	0	**7'252**	1.58	362	0
SE	3'350	633	254	0	**4'237**	0.47	371	0
US	100'000	133'000	219'000	27'000	**479'000**	1.62	103'000	70'000
Estimated total	**202'276**	**311'199**	**3'022'416**	**160'909**	**3'696'800**		**1'092'851**	**1'039'917**

Notes: Portugal not included.

Some countries are experiencing difficulties in estimating and/or apportioning off-grid domestic and non-domestic; in some markets the distinction between grid-connected

distributed and centralized is no longer clear (eg MW scale plant in the urban environment), and mini-grids using PV are also emerging, with other problems of definition.

Where definition has not been made in a national report this is shown in this table, however the totals have been estimated using the most recently available ratio from the

national reports applied to the current national data.

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[5] http://www.iea-pvps.org/isr/01.htm

Most of the solar cells produced today are made from single- and multicrystalline silicon. Fig. 2.2 shows the share of different cell types sold (Photon International 2006) and expert guess for 2006.[6] The share of amorphous silicon cells decreased in 2005 to 4.7% while the share for CdTe cells increased to 1.6% (Fawer 2006).

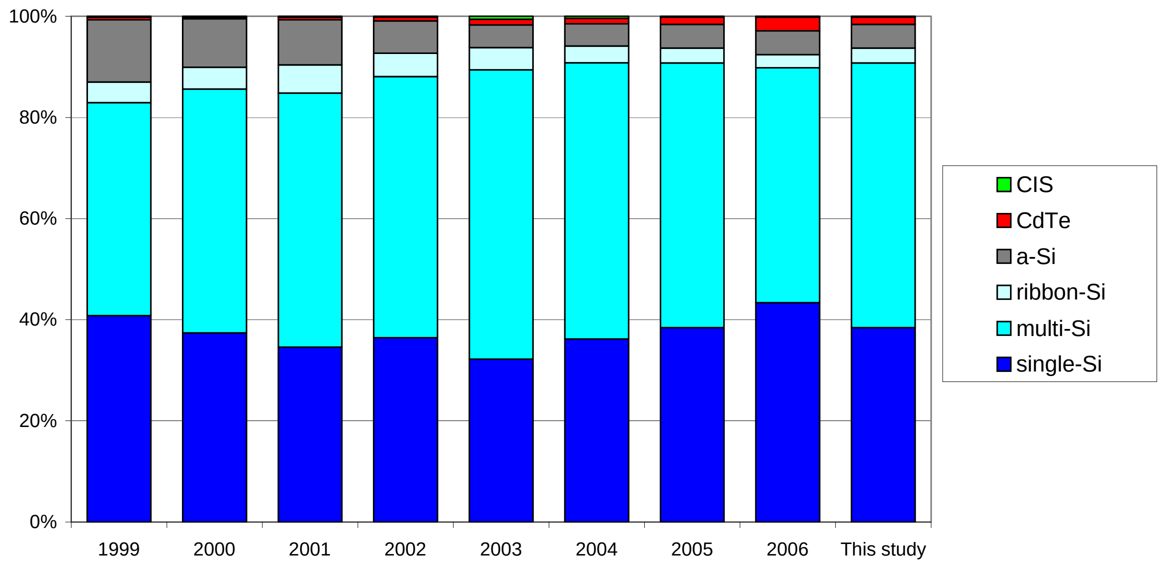

Fig. 2.2 Share of different types of photovoltaics worldwide in 1999 to 2005 and estimation for 2006 (Photon International 2006)

2.2 European PV market

The European Union photovoltaic market has reached its limits in terms of supply capacity of purified silicon for the first time in 2005. The photovoltaic industry could have produced a lot more modules if it had not been for the current shortage of purified silicon. The first figures available indicate that 645.3 MWp of new PV capacity was installed in the EU countries in 2005. This equals a growth of at least 18.2% compared to the 2004 market. The total overall installed capacity now represents approximately 1,793.5 MWp, corresponding to the needs in electricity of 600,000 households (using a hypothesis of an average annual household consumption of 3,000 kWh per year, excluding electric heating).[7] The largest installed capacity in Europe is Germany followed by Spain.

2.3 Use in Switzerland

2.3.1 Potential electricity generation

The potential for building integrated photovoltaics (BIPV) in Switzerland has been investigated in a student thesis (Gutschner 1996). The authors calculated a potential yield of photovoltaics of 8.8 to 16 TWh electricity per year in Switzerland. Compared to the total electricity use in 1994 of about 47 TWh this could supply about one fourth of the demand.

A study of the IEA-PVPS has investigated the potential of BIPV for several countries (IEA-PVPS 2002, see Tab. 2.1). It calculates a potential production of 21 TWh/a and 5.5 TWh/a on roof and façades, respectively. This would potentially supply about 34% of the electricity demand in 1998.

6 Personal communication with Stephan Gnos and Stefan Nowak, NET AG, CH, 14.12.2006

7 www.epia.org

It has to be kept in mind that the use of such areas for photovoltaics is in competition with the use for solar collectors.

2.3.2 Situation in 2005

About 100 PV power plants are installed every year in Switzerland. The trend is to construct larger plants. In the year 2005, about 1900 grid-connected PV plants with an installed capacity of 23.8 MWp were in operation. Since the last update of this study with the reference year 2000 the installed capacity has been doubled to from1325 PV-plants and an installed capacity of 12.7MWp in 2000. The total annual electricity production in 2005 was 17'800MWh (Hostettler 2006).

The SWISSSOLAR makes an annual statistic about the market for solar cells and solar collectors. The figures for 2005 are shown in Tab. 2.3 (Jauch & Tscharner 2006).

Tab. 2.3 Market research for new solar cells installations in Switzerland (Jauch & Tscharner 2006)

		2005
		kWp
Sold installations	Sold capacity (50% import)	3980
	Installed capacity	3300
Type	Grid-connected	3450
	Off-grid	150
Capacity (grid-connected)	to $4kW_p$	212
	4 to $20kW_p$	464
	20 to $50kW_p$	959
	50 to $100kW_p$	215
	More than $100kW_p$	1450
Place (grid connected)	Dwelling	623
	Industry	393
	Agriculture	419
	Public buildings	1580
	Traffic areas	117
	Others	-

Tab. 2.4 shows the development of installed PV capacities in Switzerland. Since the first publication of this study in 1994, the capacity has increased by about 400%. The installed capacity in Switzerland has been doubled since the last update of these life cycle inventory data with the reference year 2000.

Tab. 2.4 Development of installed PV capacity in Switzerland (Jauch & Tscharner 2006)[8]

Marktbereich / Anwendung	31. Dez. 1992 kWp	31. Dez. 1993 kWp	31. Dez. 1994 kWp	31. Dez. 1995 kWp	31. Dez. 1996 kWp	31. Dez. 1997 kWp	31. Dez. 1998 kWp	31. Dez. 1999 kWp	31. Dez. 2000 kWp	31. Dez. 2001 kWp	31. Dez. 2002 kWp	31. Dez. 2003 kWp	31. Dez. 2004 kWp	31. Dez. 2005 kWp
Inselanlagen (domestisch)	1'540	1'675	1'780	1'940	2'030	2'140	2'210	2'300*	2'390*	2'480*	2'570*	2'740*	2810*	2930*
Inselanlagen (nicht domestisch)	70	100	112	143	162	184	190	200*	210*	220*	230*	260*	290*	320*
Netzgekoppelte Anlagen (verteilt)	2'200	2'900	3'600	4'050	4'850	5'950	7'630	9'420	11'220	13'340	15'140	16'440	18'440	21'240
Netzgekoppelte Anlagen (zentral)	900	1'100	1'200	1'350	1'350	1'450	1'470	1'480	1'480	1'560	1'560	1'560	1'560	2560**
TOTAL	**4'710**	**5'775**	**6'692**	**7'483**	**8'392**	**9'724**	**11'500**	**13'400**	**15'300**	**17'600**	**19'500**	**21'000**	**23'100**	**27'050**

8 http://www.solarch.ch/main/Show$Id=312$LoName=solar_frames_right.html

3 System boundaries

3.1 Introduction

The focus of this study is the use of photovoltaics in grid-connected applications in Switzerland. However, many manufacturing processes for these plants take place all over the world; they are here-with modelled for the European or North-American production. Only standard laminates and panels are investigated. Special applications, as e.g. plants integrated in newly constructed buildings explicitly designed to include this feature, are not considered. All investigated plants are assumed to be installed on existing buildings.

The market for photovoltaics is increasing considerably All production processes are steadily improved and new technologies are developed.

Due to the rapid technological development it is not possible to keep the description of all technical processes fully up-to-date. Interested readers should refer to one of the available detailed books on the market (e.g. Archer & Hill 2001).

The chains for manufacturing the different options of photovoltaic power plants analyzed in this study are described dividing them into appropriate subsystems. These options have to be characterised according to different criteria, e.g. the type of cells, installation characteristics and capacity. Thus, a wide range of possible applications is possible. Here we focus the research on the most common ones. The different criteria and combinations are explained in the following sections.

3.2 Type of application

The flexiblility feature of photovoltaics make it possible to use this technology in a range of different applications (Tab. 3.1).

Tab. 3.1 Some examples for the use of photovoltaics <Jäger *et al.* 1990>

Type of application	Examples
Solar power plants	Network supply hybrid systems hydrogen production
Supply for villages (developing countries)	Single houses health stations small enterprises
Single houses	Living houses weekend huts mountain huts caravans
Water supply plants	Pumps water treatment
Environmental technology	Control units air ventilation effluent treatment plants
Traffic engineering	Buoys lighthouses SOS-telephone
Aviation and space technology	Satellites space stations air planes
Communications engineering	Relay stations broadcast station mobile phones
Leisure time	Camping sailing entertainment technology

3.3 Type of solar cells

Today there are different types of solar cells that are used for the production of photovoltaic modules for grid-connected power plants. The following types of cells are investigated in this survey, describing production representative for European market:

Singlecrystalline silicon cells (sc-Si)

This type of cells still dominates the market together with multicrystalline cells. The share of sc-Si cells is slightly decreasing (Fig. 2.2), but it will also in future remain an important type of solar cells. The name "monocrystalline cells" is also commonly used.

Multicrystalline silicon cells (mc-Si)

In earlier publications these cells have been named as polycrystalline cells. The phrase "polycrystalline" is now only used for EG-silicon or SoG-silicon or for certain thin film materials.

Ribbon silicon cells (ribbon-Si)

Ribbon-silicon cells are directly pulled (Evergreen Solar and Schott Solar) or cast (pilot plant at ECN) from the melted silicon. The wafer itself is a multicrystalline type.

CIS cells

Different producers plan to erect large production plants for thin film CIS cells. So far the most important producers are Würth Solar (CIS with selene) and Sulfurcell (CIS with sulphur) in Germany.

CdTe cells

Also for CdTe cells there are different ongoing plans for the installation of new large production facilities. The most important producer is First Solar in the US and Germany.

Amorphous silicon cells (a-Si)

Amorphous silicon (a-Si) cells have a relatively low efficiency, which decreases in the first time of use. This type of cell is investigated with data for one production plant in the United States.

3.4 Panels and laminates

Typically, a number of solar cells are assembled in a PV panel (also called module) with an area of 1.0-2 m^2. A glass-plastic laminate encapsulates the solar cells and, in most cases, an aluminium frame is added around the outer edges. In this report we distinguish panels, which are framed, and laminates, which are unframed.

3.5 Type of installation

There are ranges of different possibilities for the installation of PV panels. Here we investigate the following basic possibilities (which may not apply to every type of cells):

Flat roof installation

The installation of modules on flat roofs is a quite common type of installation. They are used for small plants on dwellings (3 kWp) as well as for larger plants on industrial roofs or sport arenas (50 kWp).

Slanted roof, mounted

This is one of the most common types for small plants of about 3 kWp. In future this type of installation might occur less frequently because roof integrated plants allow a more aesthetic and simple installation.

Slanted roof, integrated

The solar laminates are integrated in the roof construction and thus replace the normal roof cover. The installation is possible with a simple metal construction for the panels or as solar cells roof tiles.

Façade, mounted

This type of installation is mainly used for industrial or business buildings. The non-optimum angle to the sun leads to a lower electricity production. But, the modules have a better visibility and thus they can be used as an architectural design element.

Façade, integrated

Solar panels can also be integrated in the façade and thus replace other construction materials. Different design options exist for such laminates and thus make them attractive for architects.

The main differentiating criterion between integrated and mounted plants is the intact building. If the mounted structure is removed the building is still fully usable while the removal of an integrated laminate would leave a damaged building. PV shingles are not investigated in this report.

The following type of installation is not investigated in this research work:

Open ground

Open-ground are all PV power plants, which are not erected on existing buildings. Thus, the whole mounting structure is only necessary for the PV plant. Without the plant the same area could be used for other purposes, e.g. agriculture.

Panel tracking, non-concentrating

In order to optimise the yield of photovoltaic plants, the panels can be installed on a moving construction. Thus, an optimum angle to the sunlight can be maintained over the whole day. It is possible to increase thus the yield by about 20%. But, in Switzerland this type of installation is only used for single plants and mainly for research reasons. The increased expenditure for the necessary installation is not justified by the increased yield, at least not in Switzerland and other Middle-European countries. Therefore, this type of mounting system is excluded from further investigation.

3.6 Balance of system components

Several further appliances are necessary for the construction of a photovoltaic power plant. A mounting structure is necessary to fix the panels e.g. to the roof. A lightning protection is necessary for safety reasons. Batteries might be necessary for off-grid installations. The inverter is necessary for transforming the direct current to alternating current and for connection to the normal electricity grid. Inverters are investigated for plants with capacities of 0.5 kW_p, 2.5 kW_p and 500 kW_p.

3.7 Investigated systems

Sixteen different, grid-connected photovoltaic systems are herewith studied. These are different small-scale plants of 3 kW_p capacity and operational in the year 2005 in Switzerland (see Tab. 3.2).

The plants differ according to the cell type (single- and multicrystalline silicon, ribbon-silicon, thin film cells with CdTe and CIS), and the place of installation (slanted roof, flat roof and façade). Slanted roof and façade systems are further distinguished according to the kind of installation (building integrated i.e. frameless laminate or mounted i.e. framed panel).

The actual electricity mix produced in 2005 with different types of PV power plants in several countries is also modelled.

Tab. 3.2: Overview of the types of photovoltaic 3 kWp systems investigated

Installation	Cell type	Type
Slanted roof	sc-Si	Panel
	mc-Si	Panel
	a-Si	Panel
	ribbon-Si	Panel
	CIS	Panel
	sc-Si	Laminate
	mc-Si	Laminate
	a-Si	Laminate
	ribbon-Si	Laminate
	CdTe	Laminate
Flat roof	sc-Si	Panel
	mc-Si	Panel
Façade	sc-Si	Panel
	mc-Si	Panel
	sc-Si	Laminate
	mc-Si	Laminate

Cells: sc-Si = singlecrystalline silicon, mc-Si = multicrystalline silicon
Types: Panel = mounted; Laminate = integrated in the roof construction

3.8 Investigated stages of the life cycle

3.8.1 Silicon based PV plants

All subsystems shown in Fig. 3.1 are included as individual datasets within the system boundaries for silicon based PV power plants. The process data include quartz reduction, silicon purification, wafer, panel and laminate production, manufacturing of inverter, mounting, cabling, infrastructure and 30 years of operation. The basic assumptions for each of these unit processes are described in the following chapters. We considered for each production stages as far as data are available:

- energy consumption,
- air- and waterborne process-specific pollutants at all production stages,
- materials, auxiliary chemicals, etc.
- transport of materials, of energy carriers, of semi-finished products and of the complete power plant,
- waste treatment processes for production wastes,
- dismantling of all components,
- infrastructure for all production facilities with its land use.

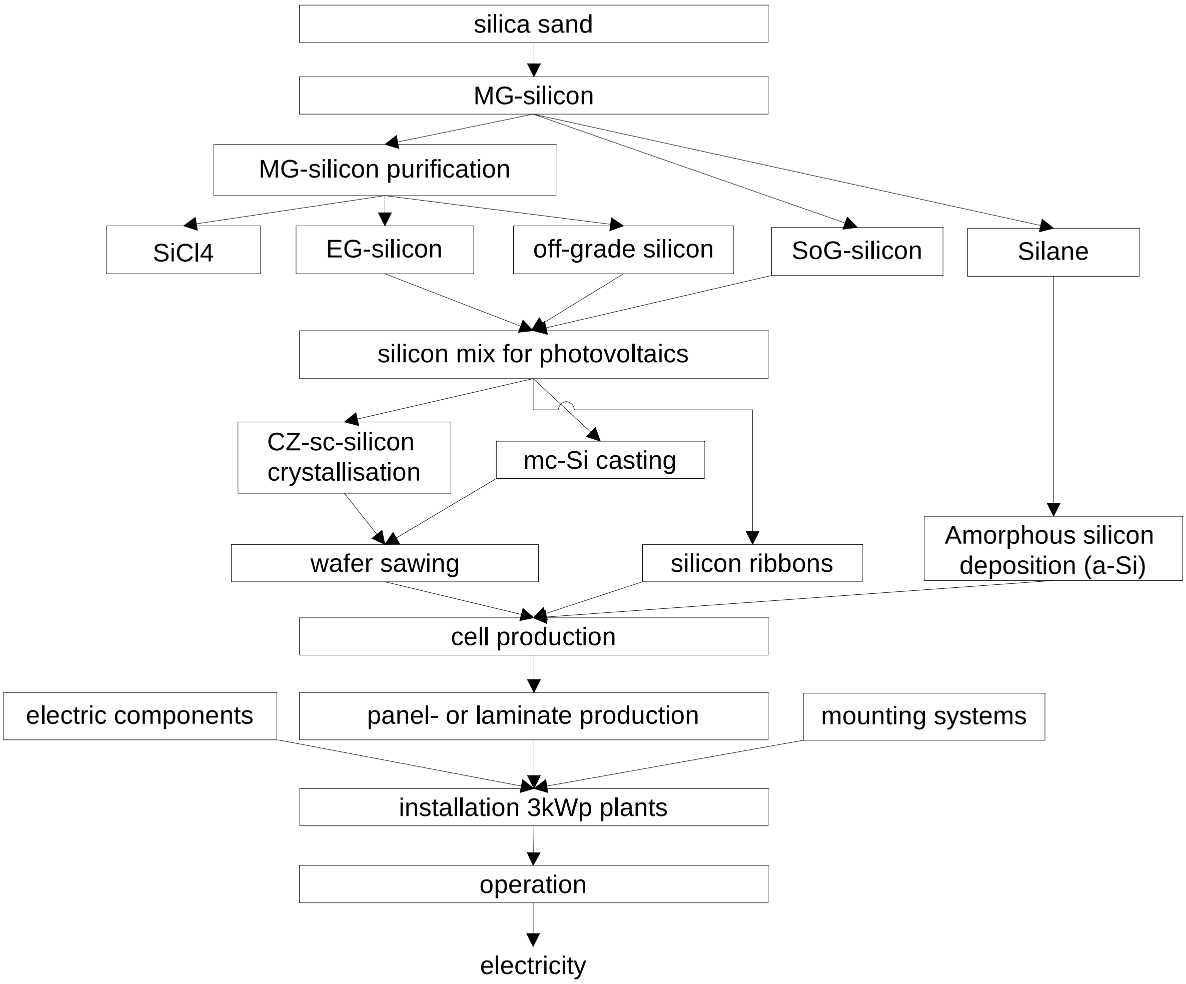

Fig. 3.1: Different sub systems investigated for the production chain of silicon cells based photovoltaic power plants installed in Switzerland. MG-silicon: metallurgical grade silicon, EG-silicon: electronic grade silicon, SoG-silicon: solar-grade silicon, a-Si: amorphous silicon

3.8.2 Thin film cells and panels

All subsystems shown in Fig. 3.2 are included within the system boundaries for thin film PV power plants. All inputs (semiconductor metals, panel materials and auxillary materials) for the production of thin film cells, laminates and panels are investigated in other reports of the ecoinvent project (Classen et al. 2007). Thus, here we only investigate the process stages starting from the laminate and panel production.

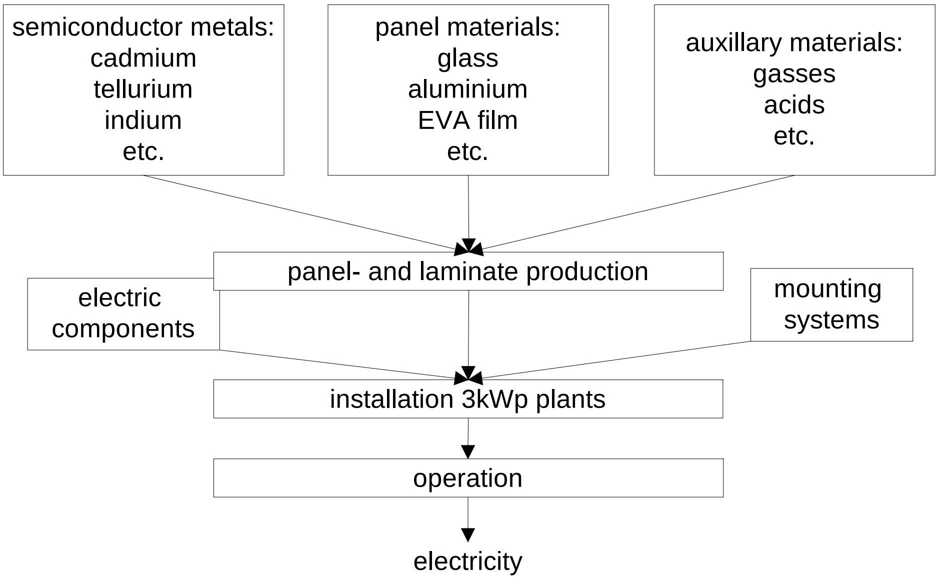

Fig. 3.2: Different sub systems investigated for thin film (CIS and CdTe) photovoltaic power plants installed in Switzerland

4 Basic silicon products

4.1 Global silicon market

The production of silicon wafers for photovoltaics is only a relatively small part of the global silicon market (Fig. 4.1). The basic product for this industry is metallurgical silicon (MG-Si), which is mainly used for aluminium and steel making. The MG-silicon is further purified for the production of electronic grade silicon (EG-silicon). By-products of this process are used for the photovoltaic industry. In 2005 there is also a new production line for solar grade silicon (SoG-Si; not included in Fig. 4.1), which is directly developed for the demand of the photovoltaic industry.

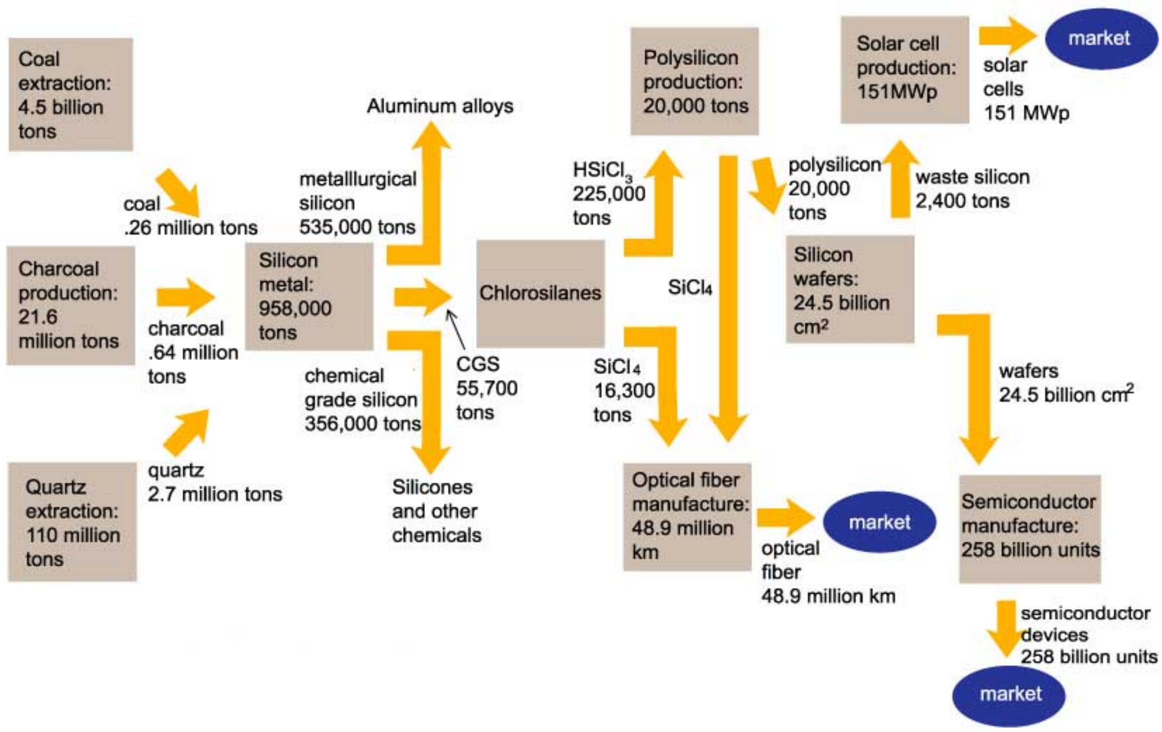

Fig. 4.1 Material flow analysis of the silicon chemistry in the year 1998 (Williams 2003)

4.2 Metallurgical grade silicon (MG-silicon)

4.2.1 Overview

About one million tonnes of MG-silicon with a purity of 98.5-99.5% was produced in the year 2000. The silicon has been used for aluminium compounds (ca. 50%), silicones (plastics) (ca. 40%) and electronics (ca. 4%). Most of the MG-silicon is produced by carbothermic reduction. The electricity use is the most important economic factors. Thus, the production takes place in countries with low electricity prices and a secure supply. The most important producers are in Norway (ELKEM), the USA, South-Africa, Brazil, France (INVENSIL) and Australia. The price is about 1.5-2.5€/kg (Woditsch & Koch 2002). Here we assume a production in Norway (electricity supply is basically from hydropower), because most data are available for this country and it represents an important share of total production. Most of the production plants have a direct access to a harbour.

The composition of the MG-silicon and other products can be found in Tab. 4.1.

Tab. 4.1 Composition of the main product and by-product from the production process of MG-silicon (Hagedorn & Hellriegel 1992:181 ff.)

MG-silicon$_{raff.}$		SiO_2-dust	
Si	99.45 %	SiC	0.4 %
SiO_2	-	SiO_2	96.5 %
Fe	0.3 %	Fe_2O_3	0.05 %
Al	0.15 %	Al_2O_3	0.2 %
Ca	0.02 %	CaO	0.1 %
Cr	33 ppm	MnO	-
Mn	74 ppm	TiO_2	-
Cu	33 ppm	Na_2O	0.1 %
Ni	130 ppm	Pb	44 ppm
Pb	0.1 ppm	K_2O	0.8 %
V	230 ppm	Cd	0.04 ppm
P	25 ppm	B	36 ppm
B	22 ppm	SO_4^{2-}	0.4 %
S	56 ppm	As	1.2 ppm
As	< 1 ppm	Cyanidion	< 0.1 %
CO	21 ppm	volatile C	1.2 %
		Chloride	0.001 %
		Fluoride	< 0.001 %
		Cr, Sb, Bi, Sn, Hg	1 ppm

ppm = *parts per million* = 0.0001 %)

4.2.2 Materials and energy carriers

Silicon is the second-most abundant element in the earth's crust after oxygen, and in natural form it is almost exclusively combined with oxygen as silicon dioxide and silicates. Silicon metal is produced in electric arc furnaces from quartz reacting at very high temperatures with reduction materials such as coal, coke, charcoal , wood chips and the furnace graphite electrodes.

The carbothermic reduction process and the basic equipment have more or less been unchanged since large-scale commercial production started in the 1930's. The following basic reaction takes place:

$$SiO_2 + 2\,C \rightarrow Si_{met.} + 2\,CO$$

The products of the process are high silicon alloy, condensed silica fume and recoverable heat energy.

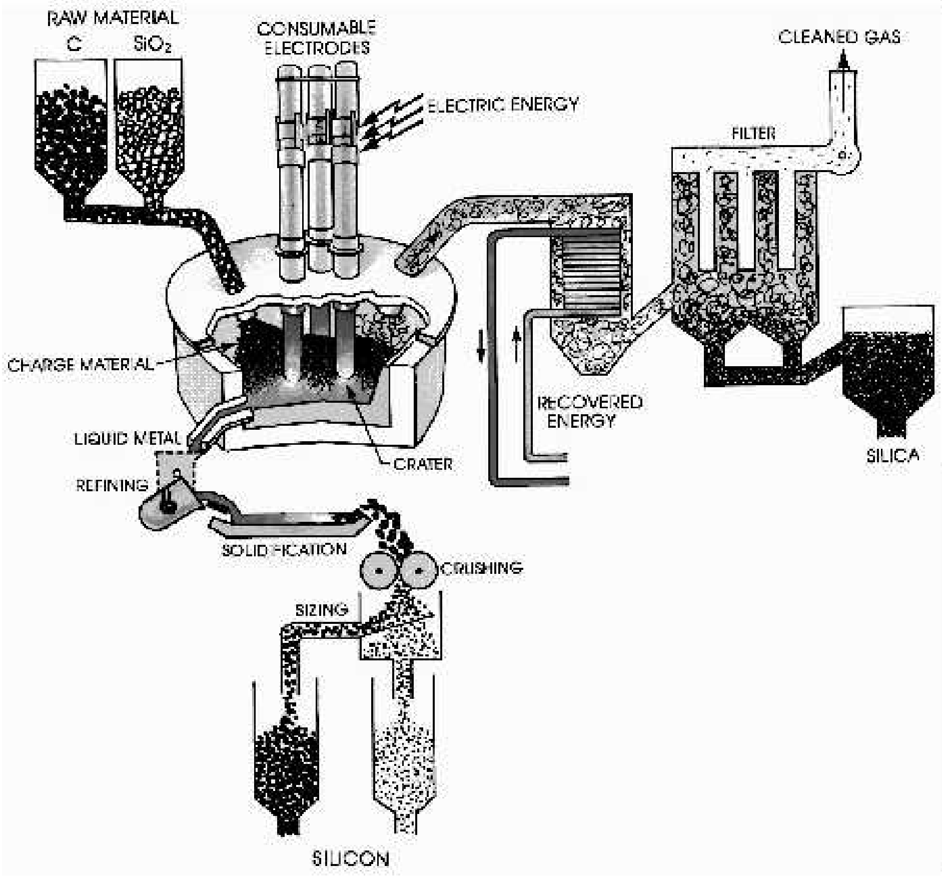

Fig. 4.2 Principle of Metallurgical Silicon Production (www.elkem.no)

The basic elementary flows for this process are listed in Tab. 4.2. Burning a part of the wood gases provides a part of the process energy. In Norway only small amounts of charcoal are used (60'000 t per year). Most of the carbon is provided by coke and coal with a total amount of one million tonnes. Charcoal is imported from Asia and South-America (Eikeland et al. 2001). The used charcoal is often not produced in sustainable forestry and thus it cannot be assumed neutral for the carbon balance. Here we assume only a small share of charcoal, which is modelled with an input of wood from European forests, and thus the associated impacts do not play an important role.

In other countries, production processes and sources of electricity might differ from Norway. In Brazil and Australia an important share of carbon is provided with charcoal and wood chips. Also in the US wood chips are used increasingly.[9] Besides, electricity is mostly based on coal in Australia and USA, whereas hydro covers a large share of the Brazilian mix.

[9] Personal communication Eric Williams, 12.2002.

Tab. 4.2 Materials used for the carbothermic reduction to MG-silicon per tonne MG-Si

		<Häne et al.1991>	(Hagedorn & Hell-riegel 1992)	EU[9]	US[9]	(IPPC 2001)	(Zulehner et al. 2002)	**This study**
Quartz	kg	2700	2900	n.d.	n.d.	2600	2900-3100	**2700**
Coal	kg	1400 [1])	600	560	370	1150-1500 [1])	1200-1400 [1])	**800**
Petroleum coke	kg	as coal	400	370	500	as coal	as coal	**500**
Wood chips	kg	n.d.	1500	1300	1750	1000-2000	1700-2500	**1350**
Charcoal	kg	n.d.	400	370	250	[3])	[3])	**170** [4])
Total energy carriers	kg	1400	2900	2600	2870	2150-3500	2900-3900	**2820**
Graphite electrodes	kg	90	90			100	120-140	**100**
Oxygen for refinery	kg	n.d.	20					**20**

[1]): incl. petroleum coke, [3]) included in the figure for wood chips, [4]) estimation for Norway

n.d. no data

Tab. 4.3 shows the total energy consumption of the process per tonne of MG-silicon.

The cumulative energy demand (CED), fuels, corresponds thereby to the total fuel consumption shown in Tab. 4.2. Different investigations show absolute figures in the same order of magnitude. The exhaust gas from the process contains about 50-60% of the energy input.

There are different options to reduce this energy use further. In a factory of Elkem the waste heat is recovered for electricity production and covers thereby 20% of the consumption (Elkem 2002). In other plants the waste heat is fed into a heating net. In order to account for these options, the electricity is estimated to be in the lower range of the shown figures with 11 kWh/kg. The Norwegian electricity mix is applied.

Tab. 4.3 Total energy consumption for the production of one tonne MG-silicon (kWh/t MG-Si)

	<Häne et al. 1991>	(Hagedorn & Hell-riegel 1992)	(IPPC 2001)	(Zulehner et al. 2002)	This study
Process, electricity	13 490	13 000			
Auxiliary energy, electricity	890	890			
CED, electricity	132 [1)]	14 556	10’800-12’000	12’500-14’000	11’000
CED, fuels	n.d.	11 403	10’120-13’200		See Tab. 4.2

1) production of sand briquettes

The waste heat of the process does not correspond directly to the used energy carriers, because the reduction of quartz is endothermic. Thus, a part of the energy is contained in the reduced silicon. About 217.4 kcal/mol (7.08 kWh/kg or 25 MJ/kg) of energy is contained in the produced MG-silicon, and has therefore been subtracted from the theoretical waste heat production <CRC 1985>.

4.2.3 Emissions

The exhaust from the process passes through a bag filter, in order to recover SiO_2-dust (also so-called amorphous silica acid). This is converted for the industry of building materials to mortar, heat-insulating materials etc.. Per ton of MG-silicon 300-750 kg SiO_2-dust result as a by-product, which is not taken into account for the modelling.

Other emissions species to the atmosphere are combustion products of the reducing agents, which were oxidized in the furnace by ambient air. Per ton MG-silicon 200,000 kg of ambient air are used. The air emissions are shown in Tab. 4.4. The CO_2-emissions are calculated according to the input of the different fuels. In (Eikeland et al. 2001) the CO_2 emissions, not containing biogenic carbon, are reported to be 4 kg/kg MG-Si. Besides CO_2, SO_2 and NOx, further emission species are investigated in the environmental report (Elkem 2001). The emissions for the five silicone producing plants (Meraker, Bremanger, Fiskaa, Salten and Thamshavn) are derived with an extrapolation of the CO_2 emissions, because data per amount of product were not available. All plants are located in Norway in low-density populated areas at the coast (Elkem 2002).

Tab. 4.4 Air emissions and by-products during MG-silicon-Production (Hagedorn & Hellriegel 1992: p.185, IPPC 2001)

Emission	kg/tonne MG-Si	Remarks
By-products		
SiO_2-dust	300-400	Used in the construction sector (IPPC 2001)
Slag	20-30	Disposal in landfill (IPPC 2001:544)
Air emissions		
SiO_2-dust	7.8	Own calculation with (Elkem 2001), 0.4-2 kg according to (IPPC 2001:535), Estimation >10nm because process emissions
CO_2	6'900 (not clear if including biogenic CO_2)	Own calculation for fossil CO_2 in Tab. 4.6: 2.4kg CO_2/kg-coke, 0.73×44/12×1000=2676kg CO_2/t-hard coal and for biogenic CO_2: 2.93kg CO_2/kg-charcoal, 2.04 kg CO_2/kg wood chips
SO_2	12.2	Own calculation after (Elkem 2001)
H_2S	<< 1	Assumed 0.5 kg/t
CO	2	
F	<< 1	Assumed as HF
NO_x	9.8	Own calculation with (Elkem 2001)

Heavy metals are mostly bound in the main product MG-Si, and in the by-products slag and SiO_2 dust. The slag is disposed off in a inert material landfill (IPPC 2001:544). The composition of the slag can be found in Tab. 4.5.

Information about effluents and emissions to water are rare. Emissions of PAHs, VOCs, dioxins and heavy metals have been measured, but not recorded because they are regarded as non-relevant (Elkem 2002).Thus, it was not possible to consider them for the life cycle inventory.

Tab. 4.5 Composition of slag from MG-silicon production (IPPC 2001) and assumption for this study.

	Range	This study
Si or FeSi	20-30%	25%
SiO_2	5-20%	10%
SiC	20-40%	30%
CaO	25-40%	25%
Al_2O_3	3-35%	10%

4.2.4 Life cycle inventory of MG-silicon

Tab. 4.6 shows the unit process raw data for the production of MG-silicon. The production of MG-silicon (metallurgical grade) with a purity of over 99% is based on carbothermal reduction of silica sand using petrol coke, charcoal and wood chips as reduction agents. The consumption of reduction agents, the electricity use, the quartz input (represented by silica sand), and the emission of air- and waterborne pollutants (CO_2, SO_2 and trace elements emitted with SiO_2 dust) are included in the inventory. The major part of the production in Europe takes place in Norway, but the exact share is not known. The Norwegian electricity mix (with a high share of hydro power) was considered for the inventory. Other producers in France, which use mainly nuclear power, could not be considered because data were not available.

An issue of concern, which could not be investigated, is the use of charcoal in this process that originates from Asia or South America and might have been produced from clear cutting rainforest wood (Eikeland et al. 2001).

Different types of elements emitted as particles are estimated with the shares shown in Tab. 4.1 for SiO_2-dust. The emission of bismuth (Bi) with SiO_2-particle emissions is not considered. Transports are calculated with standard distances. Exceptions are the transport distance for silica sand and the transport of charcoal by ship from South-East Asia. The data can be considered as quite reliable because of the well-established technology and the good documentation, e.g. in environmental reports.

Improvement options for the process are mainly a further reduction of energy consumption by heat recovery, reduction of emissions with environmental technology and use of sustainable biogenic carbon sources instead of fossil carbon sources (Elkem 2002).

Tab. 4.6 Unit process raw data of MG-silicon production

	Name	Location	InfrastructureProcess	Unit	MG-silicon, at plant	Uncertainty	StandardDeviation95	GeneralComment
	Location				NO			
	InfrastructureProcess				0			
	Unit				kg			
product	MG-silicon, at plant	NO	0	kg	1.00E+0			
technosphere	electricity, medium voltage, at grid	NO	0	kWh	1.10E+1	1	1.10	(2,2,2,1,1,3); Literature, lower range to account for heat recovery
	wood chips, mixed, u=120%, at forest	RER	0	m3	3.25E-3	1	1.10	(2,2,2,1,1,3); Literature, 1.35 kg
	hard coal coke, at plant	RER	0	MJ	2.31E+1	1	1.10	(2,2,2,1,1,3); Literature, coal
	graphite, at plant	RER	0	kg	1.00E-1	1	1.10	(2,2,2,1,1,3); Literature, graphite electrodes
	charcoal, at plant	GLO	0	kg	1.70E-1	1	1.10	(2,2,2,1,1,3); Literature
	petroleum coke, at refinery	RER	0	kg	5.00E-1	1	1.10	(2,2,2,1,1,3); Literature
	silica sand, at plant	DE	0	kg	2.70E+0	1	1.10	(2,2,2,1,1,3); Literature
	oxygen, liquid, at plant	RER	0	kg	2.00E-2	1	1.29	(3,4,3,3,1,5); Literature
	disposal, slag from MG silicon production, 0% water, to inert material landfill	CH	0	kg	2.50E-2	1	1.10	(2,2,2,1,1,3); Literature
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,2,1,3,3); Estimation
	transport, transoceanic freight ship	OCE	0	tkm	2.55E+0	1	2.10	(4,5,na,na,na,na); Charcoal from Asia 15000km
	transport, lorry >16t, fleet average	RER	0	tkm	1.56E-1	1	2.10	(4,5,na,na,na,na); Standard distance 50km, 20km for sand
	transport, freight, rail	RER	0	tkm	6.90E-2	1	2.10	(4,5,na,na,na,na); Standard distance 100km
emission air, low population density	Heat, waste	-	-	MJ	7.13E+1	1	1.10	(2,2,2,1,1,3); Calculation based on fuel and electricity use minus 25 MJ/kg
	Arsenic	-	-	kg	9.42E-9	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Aluminum	-	-	kg	1.55E-6	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Antimony	-	-	kg	7.85E-9	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Boron	-	-	kg	2.79E-7	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Cadmium	-	-	kg	3.14E-10	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Calcium	-	-	kg	7.75E-7	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Carbon monoxide, biogenic	-	-	kg	6.20E-4	1	5.10	(3,4,3,3,1,5); Literature
	Carbon monoxide, fossil	-	-	kg	1.38E-3	1	5.10	(3,4,3,3,1,5); Literature
	Carbon dioxide, biogenic	-	-	kg	1.61E+0	1	1.10	(2,2,2,1,1,3); Calculation, biogenic fuels
	Carbon dioxide, fossil	-	-	kg	3.58E+0	1	1.10	(2,2,2,1,1,3); Calculation, fossil fuels
	Chromium	-	-	kg	7.85E-9	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Chlorine	-	-	kg	7.85E-8	1	1.61	(3,4,3,3,1,5); Literature
	Cyanide	-	-	kg	6.87E-6	1	1.61	(3,4,3,3,1,5); Estimation
	Fluorine	-	-	kg	3.88E-8	1	1.61	(3,4,3,3,1,5); Literature, in dust
	Hydrogen sulfide	-	-	kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Hydrogen fluoride	-	-	kg	5.00E-4	1	1.61	(3,4,3,3,1,5); Estimation
	Iron	-	-	kg	3.88E-6	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Lead	-	-	kg	3.44E-7	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Mercury	-	-	kg	7.85E-9	1	5.10	(3,4,3,3,1,5); Literature, in dust
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.60E-5	1	1.61	(3,4,3,3,1,5); Literature
	Nitrogen oxides	-	-	kg	9.74E-3	1	1.52	(3,2,2,1,1,3); Calculation based on environmental report
	Particulates, > 10 um	-	-	kg	7.75E-3	1	1.52	(3,2,2,1,1,3); Calculation based on environmental report
	Potassium	-	-	kg	6.20E-5	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Silicon	-	-	kg	7.51E-3	1	5.10	(3,4,3,3,1,5); Literature, SiO2 in dust
	Sodium	-	-	kg	7.75E-7	1	5.10	(3,4,3,3,1,5); Literature, in dust
	Sulfur dioxide	-	-	kg	1.22E-2	1	1.13	(3,2,2,1,1,3); Calculation based on environmental report
	Tin	-	-	kg	7.85E-9	1	5.10	(3,4,3,3,1,5); Literature, in dust

4.3 Silicon carbide

Silicon carbide (SiC) is a ceramic compound of silicon and carbon that is manufactured on a large scale for use mainly as an abrasive but also occurs in nature as the extremely rare mineral moissanite. The simplest manufacturing process is to combine silica sand and carbon at a high temperature, between 1600 and 2500 °C.

Silicon carbide is used during wafer sawing. Other possible uses are:

- Abrasive for grinding, cutting and polishing

- Ceramic and refractory products
- Filler in metals, plastics and building material

The unit process raw data are based on literature data (de Wild-Scholten & Alsema 2007; Liethschmidt 2002). The emissions of CO_2 have been calculated from the amount of fuels used considering that a part of the carbon enters into the product. Other emission data for 2004 were available for the company Kollo Silicon Carbide b.v. [10] in the Netherlands (EEA 2007). These data have been used to extrapolate the amount of pollutants from the total CO_2 emissions. Tab. 4.7 shows the literature data (three right columns) and the estimated life cycle inventory. Each literature source is cited at the bottom of the right columns.

Tab. 4.7 Unit process raw data of silicon carbide

	Name	Location	InfrastructureProcess	Unit	silicon carbide, at plant	UncertaintyType	StandardDeviation	GeneralComment	silicon carbide, at plant	Kollo silicon carbide b.v.	silicon carbide, at plant
	Location				RER				RER	NL	RER
	InfrastructureProcess				0				0	2004	0
	Unit				kg				kg	a	kg
product	silicon carbide, at plant	RER	0	kg	1.00E+0						
technosphere	petroleum coke, at refinery	RER	0	kg	1.09E+0	1	1.09	(2,2,1,1,1,3); de Wild 2007, Internet	1.09E+0		1.50E+0
	silica sand, at plant	DE	0	kg	1.77E+0	1	1.09	(2,2,1,1,1,3); de Wild 2007, Internet	1.77E+0		1.55E+0
	sodium chloride, powder, at plant	RER	0	kg	7.00E-3	1	1.09	(2,2,1,1,1,3); de Wild 2007, Internet	7.00E-3		
	wood chips, mixed, u=120%, at forest	RER	0	m3	1.90E-4	1	1.09	(2,2,1,1,1,3); de Wild 2007, Internet	1.90E-4		
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation			1.00E-11
energy	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	8.60E+0	1	1.22	(1,2,1,1,3,3); Liethschmidt 2002			8.60E+0
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.04E-1	1	2.09	(4,5,na,na,na,na); Standard distance 50km, 20km for sand			1.06E-1
	transport, freight, rail	RER	0	tkm	1.18E-1	1	2.09	(4,5,na,na,na,na); Standard distance 100km			1.50E-1
waste	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	2.00E-1	1	1.24	(3,2,1,1,3,3); Rough estimation			2.00E-1
emission air, high population density	Heat, waste	-	-	MJ	7.10E+1	1	1.09	(2,2,1,1,1,3); Calculation for petroleum coke, wood chips and electricity	4.01E+1		8.51E+1
	Carbon dioxide, fossil	-	-	kg	1.90E+0	1	1.09	(2,2,1,1,1,3); Calculation for burning of petroleum coke not including carbon in the product	1.90E+0		2.88E+0
	Carbon dioxide, biogenic	-	-	kg	6.49E-2	1	1.09	(2,2,1,1,1,3); Calculation for wood chips	6.49E-2	136000000	0
	Ammonia	-	-	kg	2.02E-4	1	1.22	(2,2,1,1,1,3); Kollo silicon 2004, environmental report		14500	
	Nitrogen oxides	-	-	kg	1.44E-3	1	1.51	(2,2,1,1,1,3); Kollo silicon 2004, environmental report		103000	
	Sulfur dioxide	-	-	kg	7.10E-3	1	1.09	(2,2,1,1,1,3); Kollo silicon 2004, environmental report		509000	
	Carbon monoxide, fossil	-	-	kg	8.43E-3	1	5.01	(2,2,1,1,1,3); Kollo silicon 2004, environmental report		605000	
source									*de Wild 2007*	http://eper.cec.eu.int	*Liethschmidt 2002*

4.4 Recycling of sawing slurry and production of silicon carbide and triethylene glycol

Silicon carbide and triethylene glycol are used for wafer sawing. They can be partly recycled and reused in the photovoltaic industry. Only silicon carbide, but no purified silicon is recycled from the slurry.

The unit process raw data for the recycling of sawing slurry and production of silicon carbide and triethylene glycol are shown in Tab. 4.8. All data are provided by the CrystalClear project (de Wild-Scholten & Alsema 2007).

The gate to gate inventory for recycling of slurry produced during wire sawing of silicon wafers (specific density of the input 1.75 kg/l) includes the transport of the slurry to recycling facility, electricity use and waste treatment.

The simple inventory for the production process is based on the raw material inputs. It recycles used sawing slurry from the wafer cutting process, to recover SiC and PEG (poly ethylene glycol). This recycling is usually done off-site by the slurry supplier and therefore modelled separately. Purified silicon is generally not recycled. Allocation among the products is based on the mass of all outputs.

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10 Company homepage http://www.kollosic.nl.

Tab. 4.8 Unit process raw data of recycling of sawing slurry and production of silicon carbide and triethylene glycol. Basic data published per litre of recycled slurry (right columns, de Wild-Scholten & Alsema 2007)

	Name	Location	InfrastructureProcess	Unit	silicon carbide, recycling, at plant	triethylene glycol, recycling, at plant	Uncertain	Standard Deviation 95%	GeneralComment	*sawing slurry, to recycling*
	Location				RER	RER				*RER*
	InfrastructureProcess				0	0				*0*
	Unit				kg	kg				*l*
product	silicon carbide, recycling, at plant	RER	0	kg	1.00E+0	0				0.62
	triethylene glycol, recycling, at plant	RER	0	kg	0	1.00E+0				0.64
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	7.86E-1	7.86E-1	1	1.07	(2,2,1,1,1,na); Company data	1.10E+0
	transport, lorry >16t, fleet average	RER	0	tkm	2.63E-1	2.63E-1	1	2.09	(4,5,na,na,na,na); distances to recycling facility 200km + 50 km for disposals	
	silicone plant	RER	1	unit	1.00E-11	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation	
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	4.29E-2	4.29E-2	1	2.02	(3,1,1,1,5,3); treatment, silicon carbide	6.00E-2
	disposal, antifreezer liquid, 51.8% water, to hazardous waste incineration	CH	0	kg	7.14E-2	7.14E-2	1	2.02	(3,1,1,1,5,3); treatment, polyethylene glycol	1.00E-1
	disposal, sludge, pig iron production, 8.6% water, to residual material landfill	CH	0	kg	1.36E-1	1.36E-1	1	2.02	(3,1,1,1,5,3); final disposal, Si + Fe sludge	1.90E-1
emission air	Heat, waste	-	-	MJ	2.83E+0	2.83E+0	1	1.25	(3,3,2,3,1,5); Calculation	
source										*de Wild 2007*
	produced silicon carbide, silicon and iron mix			kg						0.14
	total products			kg						1.4
	slurry input to recycling			kg						1.75

4.5 Meta information of basic silicon products

Tab. 4.9 show the EcoSpold meta information of basic silicon products investigated in this chapter.

Tab. 4.9 EcoSpold meta information of basic silicon products

ReferenceFunction	Name	silicon carbide, at plant	silicon carbide, recycling, at plant	triethylene glycol, recycling, at plant	MG-silicon, at plant
Geography	Location	RER	RER	RER	NO
ReferenceFuncti	InfrastructureProcess	0	0	0	0
ReferenceFuncti	Unit	kg	kg	kg	kg
	IncludedProcesses	Gate to gate inventory for production of silicon carbide from silica sand. Including materials and electricity use. Some emissions to air from the process.	Gate to gate inventory for recycling of slurry produced during wire sawing of silicon (Spec. Weight of input 1.75kg/l). Includes transport to recycling facility, electricity use and waste treatment.	Gate to gate inventory for recycling of slurry produced during wire sawing of silicon (Spec. Weight of input 1.75kg/l). Includes transport to recycling facility, electricity use and waste treatment.	Gate to gate inventory for production of MG-silicon from silica sand including materials, energy use, wastes and air emissions. Emissions to water are not available.
	LocalName	Siliziumkarbid, ab Werk	Siliziumkarbid, Recycling, ab Werk	Triethylenglykol, Recycling, ab Werk	MG-Silizium, ab Werk
	Synonyms	silicon monocarbide // carborundum // carbolon	silicon monocarbide // carborundum // carbolon	PEG//polyethylene glycol	metal grade silicon
	GeneralComment	Life cycle inventory for the production process based on raw material inputs and data for energy use and emissions.	The simple inventory for the production process is based on the raw material inputs. It recycles used sawing slurry from the wafer cutting process, to recover SiC and PEG (poly ethylene glycol). This re-cycling is usually done off-site by the slurry supplier and therefore modelled separately. Silicon is generally not recycled. Allocation among the products is based on the weight of all outputs.	The simple inventory for the production process is based on the raw material inputs. It recycles used sawing slurry from the wafer cutting process, to recover SiC and PEG (poly ethylene glycol). This re-cycling is usually done off-site by the slurry supplier and therefore modelled separately. Silicon is generally not recycled. Allocation among the products is based on the weight of all outputs.	MG-silicon with a purity of 99%. Used for the production of aluminium compounds, silicones and semiconductors. For the use in semiconductors further purification is necessary.
	Category	chemicals	chemicals	chemicals	metals
	SubCategory	inorganics	inorganics	organics	extraction
	Formula	SiC	SiC	C2H6O2	Si
	StatisticalClassification				
	CASNumber	409-21-2	409-21-2	112-27-6	7440-21-3
TimePeriod	StartDate	2000	2005	2005	2000
	EndDate	2006	2006	2006	2002
	OtherPeriodText	Time of publication.	Time of publication and data investigation.	Time of publication and data investigation.	Time of publication.
Geography	Text	Estimation for Europe. Emissions data for NL plant.	Data for European companies.	Data for European companies.	Production plants in NO.
Technology	Text	Average technology data for 4 companies.	Average technology.	Average technology.	Modern technology, waste heat is partly recovered and used for electricity generation and/or district heating.
Representativen	Percent	10	10	10	50
	ProductionVolume	Not known.	Not known.	Not known.	1'000'000t in 2000. Most of European plants are located in NO.
	SamplingProcedure	Literature and internet. Average data from 4 companies.	Literature and internet. Average data from 3 companies.	Literature and internet. Average data from 3 companies.	Publication of plant specific data in a European survey.
	Extrapolations	Emission data extrapolated with total CO2 emissions.	none	worldwide data	Air emissions of different pollutants are extrapolated from environmental reports.

5 Purified silicon and crystalline silicon products

5.1 Overview

Before silicon can be used for various semiconductor applications, including solar cells, it needs to be further purified, to impurity levels of 0.01 to 0.0001 ppmw (parts per million by weight). Depending on the impurity concentrations this material is classified as solar grade (SoG, 0.01 ppmw) silicon or electronic grade (EG, 0.0001 ppmw) silicon. Because this purified silicon material is usually produced in polycrystalline form, a commonly used name within the industry for both EG- and SoG-silicon is "poly-silicon". This poly-silicon is the starting material for production of crystalline silicon wafers, either for electronic or for photovoltaic applications.

Historically the poly-silicon production was largely supplied to the manufacturers of integrated circuits and other electronic components. Because the impurity requirements for photovoltaic applications are less stringent than for integrated circuits, in the past the PV industry mostly relied on the "off-grade" poly-silicon that was not suitable for the electronics industry. Also rejects from the subsequent crystallisation process and other silicon "scrap" was re-used for photovoltaic wafer production.

Due to the strong growth in demand from PV industry over the past few years several alternative methods have been developed to produce poly-silicon specifically for photovoltaic applications. For example EG-silicon producers have started to produce specifically for the PV industry, with the same equipment as used for EG silicon, but with slightly adapted production conditions. We will call this process "modified Siemens" process, after the name of the deposition reactor. The resulting material is usually called "solar grade silicon", but this name is rather ambiguous as also material produced by other purification processes is called solar grade. For this reason we name it here "solar-grade, modified Siemens process".

Apart from the conventional route for solar grade silicon production by way of the Siemens process a number of novel processes for solar grade silicon have been developed over time, for example by using a Fluidized Bed Reactor for the deposition process. Another alternative is to use a metallurgical process to upgrade MG-silicon or silica to a solar grade silicon material. The expectation is that these new solar-grade silicon processes will be able to deliver silicon material with a quality that is suitable for PV production and at lower costs. Fig. 5.1 shows a number of possibilities for the provision of poly-silicon for photovoltaic wafers.

In summary we can say that are two ways to distinguish purified silicon production:

1) by material quality, i.e. electronic-grade or solar-grade. Typical impurity levels for electronic grade material are around 0.001 ppmw, while for solar silicon they are around 0.01 ppmw (Hesse, 2004).
2) by process route: i.e. standard Siemens, modified Siemens, Fluidized Bed Reactor, etc.

Of course each process will be most suitable for a specific material quality, for example the standard Siemens process will be used to produce electronic grade material, while the modified Siemens and Fluidized Bed Reactor processes are primarily suitable to deliver solar-grade material.

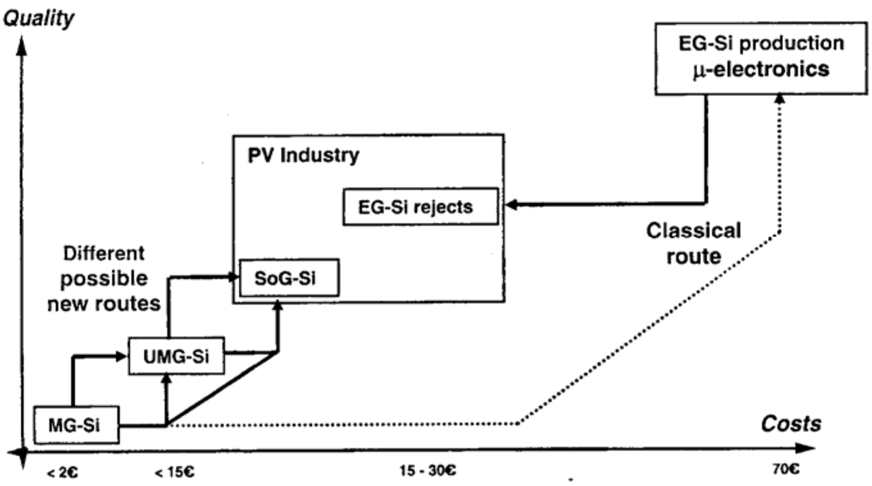


Fig. 5.1 Different supply routes for mc-Silicon used in photovoltaic applications and prices in euro/kg (Sarti & Einhaus 2002), UMG-Si – upgraded metallurgical grade silicon

Fig. 5.2 shows the amount of EG-silicon and “Solar” silicon[11] produced in 2005. The total production amounted to 32000 t. About 45% (Solar-Si) is specifically produced for the photovoltaics industry. The most important producers are Hemlock, Wacker and Tokuyama (Aulich 2006). A number of manufacturers have started with alternative solar-grade processes (i.e. not based on the Siemens technology) at a pilot-scale in 2005-2006 and it is expected that the first commercial-scale deliveries of these materials will start in 2007.

Of the 32’000 tonnes of purified silicon supplied in 2005 about 13’300 tonnes (40%) was used by the PV industry. From the latter share only 700 tonnes (5%) was off-grade material, the rest was newly produced silicon (Aulich 2006; Rogol 2005). The newly produced “solar” silicon is probably produced to a large extent by means of modified Siemens process because this is cheaper. However producers of monocrystalline wafers and cells may also choose for standard EG-material with its higher quality. Reliable data in this area are very difficult to obtain.

[11] Note that in this figure “solar” material only refers to a material quality; probably more than 90% of this material has actually been produced by means of a modified Siemens type of process. New solar grade processes have still a very small production capacity.

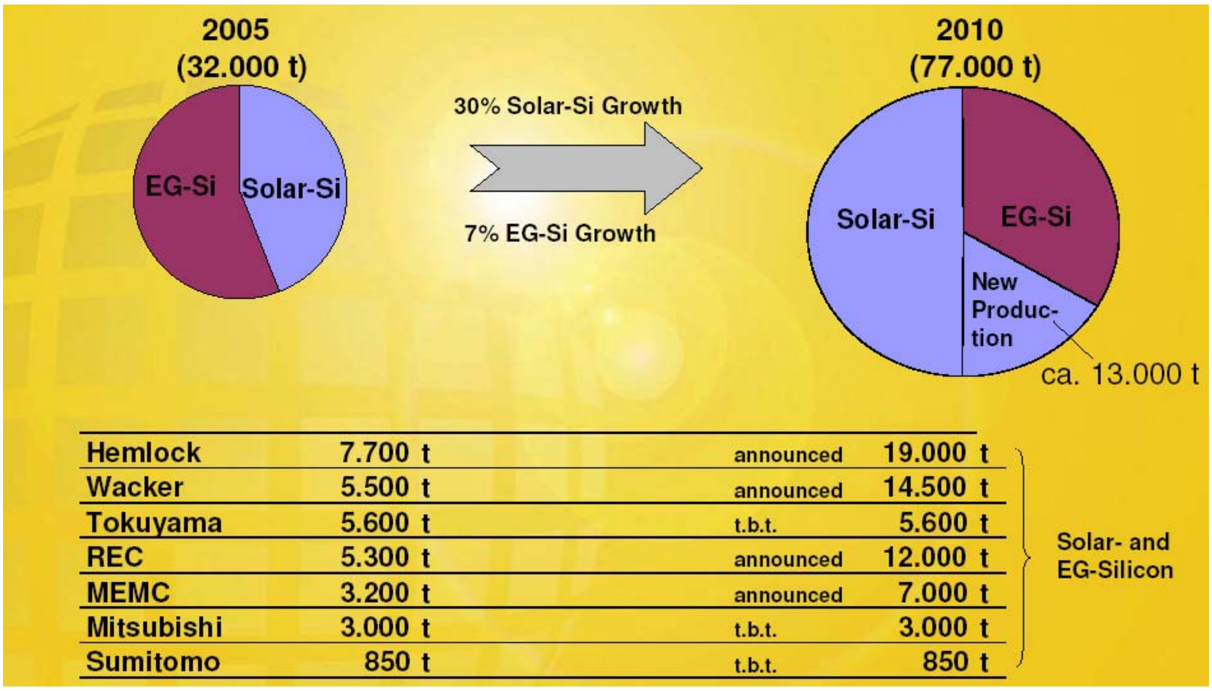


Fig. 5.2 **EG- and Solar-Silicon production in 2005 and expected growth until 2010 (Aulich 2006)**

Seven producers have a market share of about 90%. The most important process for silicon purification is the trichlorosilane process. The most important producers and their production process are shown in Tab. 5.1.

Tab. 5.1 **EG-silicon producers and the used production processes (Bernreuter 2001; 2005; Wacker 2002; Woditsch & Koch 2002)**

Company	Process
ASiMi, US	TCS equilibrium reaction in fluidised bed reactor to silane and $SiCl_4$, reaction with hydrogen to TCS, by-product SiH_4 .
Chisso, JP	Reduction of trichlorosilane with zinc
Elkem, NO	Slagging, etching, refining of MG-silicon
Hemlock, US	Complex chlorosilane-chemical facility. MG-Si reaction with HCl to trichlorosilane ($HSiCl_3$, TCS), purification of TCS, reaction with hydrogen, by-products are chlorosilane and silica acid.
Invensil, FR	Plasma purification of MG-silicon
JSSi, DE	tube reactor with feed material silane
MEMC, IT/US	Silane production with hexafluorosilicic acid (H_2SiF_6) Reaction with sodiumaluminiumhydride ($NaAlH_4$), Reaction with silane (SiH_4) to silicon and hydrogen, dehydrogenation des silicon granulate
Mitsubishi, JP/US	Not known
Sumitomo, JP	Not known
SGS, US	Fluidised bed reactor with silane
REC, US	Deposition of silane gas in fluidised bed reactor.
Tokuyama, JP	Vapour to liquid deposition of trichlorosilane
Wacker, DE	Complex chlorosilane-chemical facility. MG-Si reaction with HCl to trichlorosilane ($HSiCl_3$, TCS), purification of TCS, reaction with hydrogen, by-products are chlorosilane and silica acid.

Below we will discuss subsequently the production of EG-silicon, as produced with the standard Siemens process, then solar grade silicon, produced with a modified Siemens process, and finally a number of new solar-grade processes that are near commercial application or still under development.

5.2 Electronic grade silicon, off-grade silicon and silicon tetrachloride

5.2.1 Process

The EG-silicon is mainly used for the production of semiconductors in electronics. Historically the off-grade silicon from this process, and silicon scrap from other stages in the production chain of electronic products (Fig. 5.4), were the major sources of silicon for the PV industry. However, with the large growth in the demand from the PV industry the relative importance of this source of silicon has strongly declined, to about 5% in 2005 (Rogol 2005).

In practice EG-silicon is a product from complex chemical production plants. In the conventional route for production of EG-silicon (electronic grade) comprises three process steps:

1) the MG-silicon is converted into a gas, either trichlorosilane ($SiHCl_3$) or silane (SiH_4),
2) this gas is purified by means of distillation,
3) silicon in solid form is deposited in a Siemens reactor.

Fig. 5.3 shows the integrated silicon-based production system. It is based on the principle of multiple usage of products and raw materials in a network of optimised material loops. The producer investigated the potential suitability of by-products obtained during one production process as feedstock for parallel production processes. This saves energy and cuts resource consumption, too (Wacker 2002).

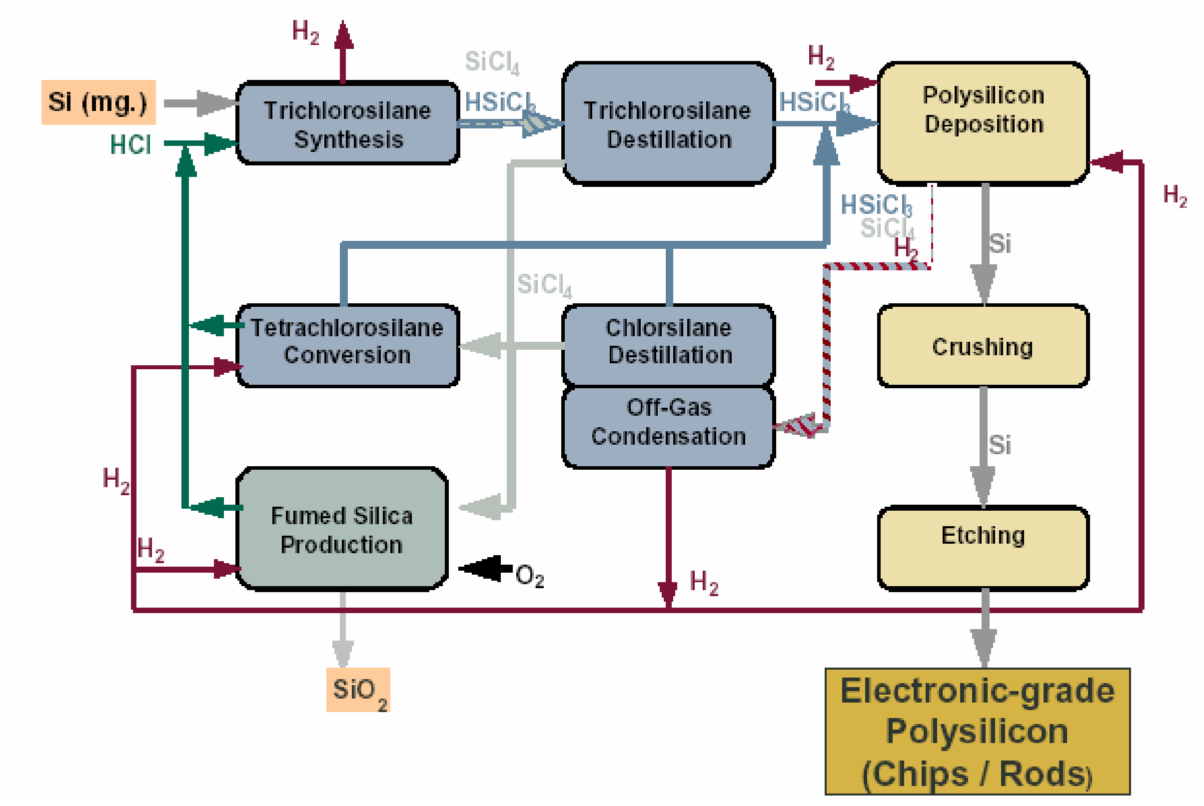


Fig. 5.3 Processing flows and used materials in the integrated silicon-based production system for EG-silicon (Hesse & Schindlbeck 2004)

The off-grade silicon for photovoltaics is a by-product in several stages of the production chain for electronic products (Fig. 5.4). Also low quality wafers from the semiconductor production might be used for the production of PV cells.

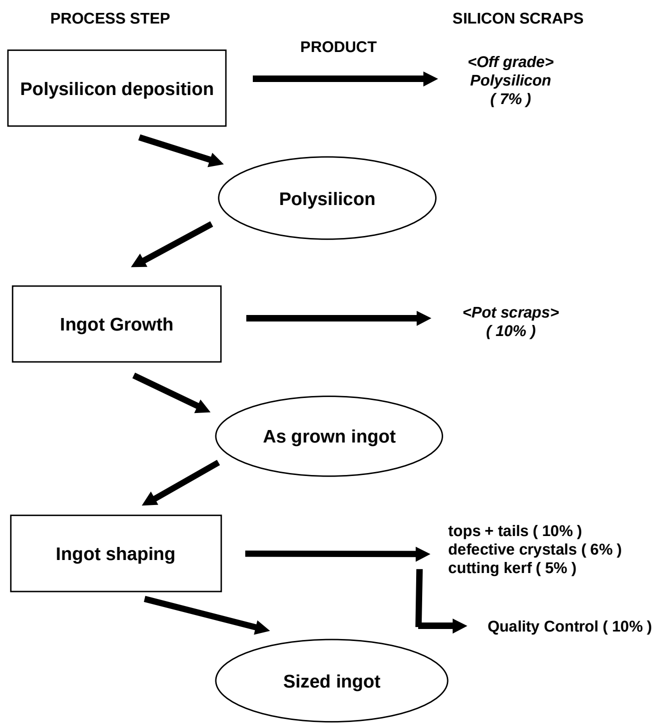


Fig. 5.4 Supply of off-grade silicon in different process stages of wafer production for electronics (Woditsch & Koch 2002). Percentage share of silicon scraps

Production of trichlorosilane

The MG-silicon is grinded to a grain size of < 0.5 mm. The powder is reacted in a fluidized bed by hydrochlorination into gaseous chlorosilane. The products trichlorosilane (TCS, $HSiCl_3$) and silicon tetrachloride (STC, $SiCl_4$) are produced according to two reactions:

$$Si_{met.} + 3\ HCl \rightarrow HSiCl_3 + H_2$$

$$Si_{met.} + 4\ HCl \rightarrow SiCl_4 + 2\ H_2$$

A by-product is dichlorosilane (DCS, H_2SiCl_2) and dichloromethylsilane (CH_3SiHCl_2). This can be used for other production processes at (Wacker 2002). Polluting metals react to chlorides, e.g $FeCl_2$, $AlCl_3$, $CaCl_2$, BCl_3, $AsCl_3$, PCl_3 and $POCl_3$ etc. The whole process takes place in reactor made from stainless steel and fitted with PTFE because TCS is not stable with air humidity. Hydrogen is separated in a gas cleaning unit. The silane phase is condensed and purified by distillation. TCS is separated in this stage from the metal chlorides.

Silicon-deposition

The purified TCS is mixed with hydrogen and than introduced into the deposition reactors. The gas is decomposed onto the surface of heated silicon rods, electrically heated to about 1100°C. The main reactions are:

$$HSiCl_3 + H_2 \rightarrow Si_{met.} + 3\ HCl$$

$$4\ HSiCl_3 \rightarrow Si_{met.} + 3\ SiCl_4 + 2\ H_2$$

Again STC is produced in this process. Fig. 5.3 shows the integrated silicon-based production system that is used to reuse the STC. Trichlorosilane (TCS) and high disperse fluosilicic acid (HDK) are produced from the STC.

5.2.2 System boundaries and allocation

The purification process provides three different products, which are used in three different economic sectors (see Fig. 5.5). The environmental impacts of the purification process have to be shared between these three coupled products. In LCA the problem how to assign the environmental impacts between different coupled products is termed as allocation problem. Different approaches how to solve this problem are possible according to the ISO-standards. One approach consists of dividing all elementary flows according to the revenue formed by the coupled products, thus the product with the highest price gets the highest environmental impacts. Another possibility is dividing the elementary flows according to mass flows or physical relationships in the system. In this case, the input of hydrogen chloride is allocated to the production of silicon tetrachloride as far as the chloride can be found in this product.

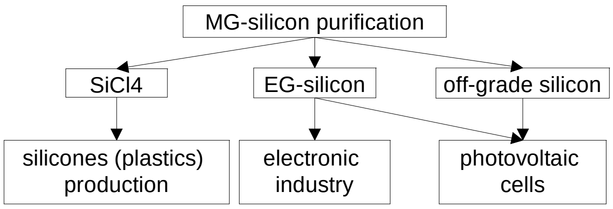


Fig. 5.5: Purification of MG-silicon delivering three different co-products

In several LCA studies of photovoltaics all inputs and outputs for the purification process of MG-silicon have been allocated to the EG-silicon (required for wafer production), because this is the main product from an economic point of view, and no flows have been allocated to the silicon tetrachloride. However, in an LCA study of vacuum insulation (based on silicic acid) inputs and outputs of the purification process have been allocated on the basis of the revenues of EG-silicon and $SiCl_4$ (Wohler & Schonhardt 2001). ISO 14041 states that, "the sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process" (International Organization for Standardization (ISO) 1998). This rule has been followed for the ecoinvent database. The inputs and outputs of the silicon purification process are shared between all three products.

The process is modelled as a multi-output process. The modelling choices are explained in Tab. 5.2. The allocation of inputs and elementary flows is based on different flow specific principles. For material inputs of MG-silicon and hydrogen chloride an allocation based on the mass of chemical elements (Si, H, Cl) in the final products has been chosen. Losses of these inputs are attributed to the main product EG-silicon because this is the economic main product. The energy input and emissions from the process are allocated only to the two purified silicon products based on economic revenues because it is assumed that these inputs would not be necessary for the sole production of $SiCl_4$. The use of some chemicals and the infrastructure, which is generally necessary for the production process, is shared between all three products based on the respective economic revenue.

This approach is a simplification, because it is herewith assumed that all off-grade silicon comes directly from the EG-silicon purification. In reality a part is formed from scraps for CZ-Si production (Czochralski grade sc-Silicon, see chapter 5.5) and wafer sawing. These scraps are sold and used directly in the casting process. Thus, a more correct modelling would be to assume also multi-output processes for these process stages. Off-grade silicon from these stages would bear a higher burden, because it already went through more production stages.

In view of the decreasing share of off-grade silicon in the supply of the PV industry (5% in 2005) the influence of this allocation problem is becoming less important for the LCA of photovoltaics.

Tab. 5.2 System boundaries and main allocation criteria for the modelling of unit process raw data of MG-silicon purification

Problem	**Modelling approach in this study**
Different producers use different production processes.	The unit process is modelled for the production process of Wacker in Germany, because for this process most of the data were available. The other important producer in Europe is MEMC in Italy, which uses a different production process (Tab. 5.1).
The process of MG-silicon purification provides different by-products (off-grade Si, TCS, STC, H_2, MG-silicon).	The price of different products is the main allocation criteria. It is assumed with 20€/kg for off-grade and 75€/kg for EG-silicon. The price for $SiCl_4$ is estimated with 15€/kg.[12]
The used MG-silicon is used for all by-products. Thus, the input must be allocated to all by-products.	The allocation is based on a mass balance and not on the price of the outputs.
Off-grade silicon, used for casting, is also a by-product of further production stages for singlecrystalline silicon (see Fig. 5.4). A difference in price or quality for these sources is not known.	It is assumed in a simplified approach that all off-grade silicon stems from the first purification stage. This means all inputs and outputs from the CZ-Si process (described in section 5.6)are allocated to the main product sc-Si and not to the off-grade silicon from these process stages.
The source of electricity supply is quite important for the assessment of the environmental impacts.	The electricity consumption is modelled with the electricity used by the German producer (Wacker 2002). No specific assumptions are taken into account for silicon produced at other plants and imported for the production of electronic products.

5.2.3 Material inputs

Not much is known about the materials used in the process stage. Nijs et al. (1997) published some data for a Japanese and a US production site based on TCS. Data by Hagedorn (1992) were aggregated including the wafer production. Later they have been disaggregated (Frischknecht et al. 1996; Hartmann 2001). These data are shown in Tab. 5.3.

The most important inputs to this process are MG-silicon, hydrochloric acid and hydrogen. Today a much higher yield from the MG-silicon than investigated by Hartmann can be expected (Hartmann 2001). The product yield from MG-silicon is estimated with 95% based on general assumptions for chemical processes. Out of this about 20% is provided as $SiCl_4$. The allocation of the inputs (incl. transport processes) is based on the silicon content in the products. MG-silicon is assumed to be transported by truck over 2000 km from Thamshavn, Norway to Germany (Wacker 2002).

Hydrochloric acid is used in large amounts and it can be partly recovered. The amount coming together with $SiCl_4$ is about 1kg HCl per 200 g of silicon. Double the amount is considered here as input in order to account for losses and regeneration efforts. High amounts of deionised water are necessary for purification processes (Wacker 2002). The amount is estimated with the average for this production site, which is 17 l/kg product. Further inputs can be seen in Tab. 5.3. For the allocation of the HCl input, the amount of chlorine in $SiCl_4$ is calculated. The rest is allocated to all products according to the prices. The purpose of high nitrogen use as reported by Nijs et al. (1997) is not clearly described and thus not taken into account here. At least it can be assumed that nitrogen is produced on-site and thus production is included in the electricity use figures.

All other inputs are allocated according to the product prices. Hydrochloric acid and hydrogen are produced in the same chemical facility. Thus no transports to the production plant are necessary.

[12] Personal communication E. Williams, UN University, JP (12.2002): He assumes a price range of 1 – 25$/kg for this type of product. There is no real market price as most of the production is used internally.

Tab. 5.3 Inputs for the production of EG-silicon per kg

		EG-Si	EG-Si	**EG-Si**	Remarks
		kg	kg	**kg**	
MG-silicon	kg	1.25 [1)]	1.15	**1.05**	By-products of MG-silicon removal are subtracted
HCl	kg	3.93 [1)]	-	**2.5**	For TCS-production
Silicon Tetra-chloride	kg	-	0.3	**-1.6**	Calculation for product output from the process
Sodium hydrox-ide	kg	-	0.5	**0.5**	For neutralization of wastes
Hydrogen	kg	0.62	0.07	**0.07**	Deposition
Nitrogen	kg		3.75	**-**	Purpose of use not clear.
PTFE	g	0.6	-	**0.6**	Fittings
PE	g	3.5	-	**3.5**	Different plastic parts
Graphite	g	0.83	-	**0.83**	Type of use not known
Cooling water	m^3	-	50	**50**	
Source		(Hartmann 2001) derived from (Hagedorn & Hellriegel 1992:141, 123)	(Nijs et al. 1997)	**This study**	

[1)] Based on information from one producer (1997).

5.2.4 Energy use

Tab. 5.4 shows different estimations for the energy use in this process. Methodological decisions influence the outcome of such an energy analysis as already discussed in Tab. 5.2. The publications use quite different system boundaries and different reference units. Sometimes important information is missing. Thus, a full comparability is not given and differences are not always easy to explain. Many studies are not based on first hand data, but on older publications. Here we tried to show only independent calculations based on first hand data and not recalculations from older studies.

Here we use the recent figures 150 kWh electricity and 160 MJ heat (Hartmann 2001). They are based on anonymous European information. It can be assumed that they refer to the production of Wacker for the production site in Burghausen (Wacker 2002) and thus the most relevant information for a European production (see Tab. 5.1). The order of magnitude is similar to other recent publication. Nevertheless the uncertainty is quite high as no first hand information was available. For the calculation of waste heat, 180 MJ/kg EG-Si is subtracted for the bound energy.

In 2001 the German producer Wacker produced 24% of the electricity with a run-of-river hydro power plant and 76% with a cogeneration gas power plant (Wacker 2002). Also all heat requirements were provided by the latter. Most of the energy is used for distillation and electro deposition. Thus, no energy use is allocated to $SiCl_4$ production.

Tab. 5.4 Energy uses for EG-Si production from MG-Si purification

Efficiency MG-Si to Si-Output	Electricity	Heat	Source
%	kWh/kg EG-Si	MJ/kg EG-Si	
n.d.	114.3	-108	(Hagedorn & Hellriegel 1992)
n.d.	58	158	<Häne et al. 1991>
n.d.	129	-	<Linton 1993>
22%	120-150	-	(Kato et al. 1997a)
n.d.	250-470	-	(Alsema et al. 1998, range of literature values)
n.d.	83	-	(Alsema 2000b) estimation for Off-grade silicon.
6-20%	300	-	(Strebkov 1999)
6-20%	250	-	(Tsuo et al. 1998)
37.8%	370	-	(Williams et al. 2002), based on literature in the 1990s
n.d.	200-250	-	(Anderson et al. 2002) production of Czochralski rods from MG-Si bei AsiMi in the USA
86.9%	150	162	(Nijs et al. 1997) TCS and STC Production from MG-Si with HCl and hydrogen in fluidized bed reactor, distillation from gas phase.
23%	101	-	(Frankl 1998)
80%	147	155	(Hartmann 2001), based on information provided in 1997, Germany, Recycling of TCS and STC in the process
95% [1])	**150**	**160**	**This study, small part allocated to the by-product $SiCl_4$**

[1]) See chapter on material inputs

5.2.5 Emissions

Not much is known about the direct process emissions. The metal chlorides from silicon purification are treated in the central waste water treatment plant. Emissions to water are estimated based on the average from one production site (Wacker 2002) and they are shown in Tab. 5.5. The allocation is based on economic criteria as a physical relationship is not known.

5.2.6 Life cycle inventory of MG-silicon purification

The life cycle inventory data are based on information available for the most important producer in Europe, located in Germany. Thus it cannot be regarded as representative for other technologies or production sites. The electricity consumption is calculated with the in-house mix of the production that uses a natural gas co-generation power plant and hydropower.

Tab. 5.5 shows the inputs, outputs and the allocation factors of the MG-silicon purification process. The meta information for this unit process is shown in Tab. 5.14. The first three lines show the co-products and their respective amounts, EG-silicon (0.68 kg), off-grade electronic grade silicon (0.084 kg) and silicon tetrachloride (1.2 kg). The next lines show the inputs required for the purification of 1 kg of MG-silicon. The three columns to the right show the allocation factors: For instance, 71.1 % of the input "MG-silicon, at plant" is allocated to the 0.68 kg of EG-silicon, 8.9 % to 0.084 kg off-grade silicon and 20 % to 1.2 kg $SiCl_4$.

The inputs and outputs described before per kg of EG-silicon are now calculated per kg of MG-silicon input. For electricity this means e.g. 150 kWh/kg EG-Si (including off-grade silicon) / 0.76 kg EG-Si/kg MG-Si = 114 kWh/kg MG-silicon input.

Tab. 5.5 Unit process raw data of MG-silicon purification. Allocation factors for the coupled products EG-silicon, off-grade silicon and silicon tetrachloride

	Name	Location	InfrastructureProcess	Unit	MG-silicon, to purification	UncertaintyType	StandardDeviation95	GeneralComment	silicon, electronic grade, at plant	silicon, electronic grade, off-grade, at plant	silicon tetrachloride, at plant
	Location				DE				DE	DE	DE
	InfrastructureProcess				0				0	0	0
	Unit				kg				kg	kg	kg
allocated products	silicon, electronic grade, at plant	DE	0	kg	6.76E-1				100	0	0
	silicon, electronic grade, off-grade, at plant	DE	0	kg	8.44E-2				0	100	0
	silicon tetrachloride, at plant	DE	0	kg	1.20E+0				0	0	100
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	4.35E+1	1	1.34	(4,4,3,3,1,5); Literature 1997	96.8	3.2	-
technosphere	MG-silicon, at plant	NO	0	kg	1.00E+0	1	1.26	(3,1,3,1,1,5); Literature 1997	71.1	8.9	20.0
	polyethylene, HDPE, granulate, at plant	RER	0	kg	6.37E-4	1	1.69	(4,4,4,3,4,5); Literature, Hagedorn, different plastics	72.0	2.4	25.6
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	2.00E+0	1	1.11	(3,na,1,1,1,na); Estimation, produced on site	48.4	1.6	50.0
	hydrogen, liquid, at plant	RER	0	kg	6.26E-2	1	1.34	(4,4,3,3,1,5); Literature 1997, produced on site	96.8	3.2	-
	tetrafluoroethylene, at plant	RER	0	kg	6.00E-4	1	1.69	(4,4,4,3,4,5); Hagedorn 1992, fittings	72.0	2.4	25.6
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	4.35E-1	1	1.34	(4,4,3,3,1,5); Literature 1997, neutralization of wastes	72.0	2.4	25.6
	graphite, at plant	RER	0	kg	6.66E-4	1	1.69	(4,4,4,3,4,5); Hagedorn 1992, graphite	72.0	2.4	25.6
transport	transport, lorry >16t, fleet average	RER	0	tkm	2.04E+0	1	2.09	(4,5,na,na,na,na); Standard distances 100km, MG-Si 2000km	71.1	8.9	20.0
	transport, freight, rail	RER	0	tkm	8.73E-2	1	2.09	(4,5,na,na,na,na); Standard distances 200km	72.0	2.4	25.6
	water, completely softened, at plant	RER	0	kg	1.29E+1	1	1.22	(2,2,1,1,3,3); Environmental report 2002	96.8	3.2	-
energy	heat, at cogen 1MWe lean burn, allocation exergy	RER	0	MJ	1.22E+2	1	1.59	(3,1,3,1,1,5); Literature 1997, basic uncertainty = 1.5	96.8	3.2	-
	electricity, at cogen 1MWe lean burn, allocation exergy	RER	0	kWh	8.66E+1	1	1.59	(3,1,3,1,1,5); Literature 1997, basic uncertainty = 1.5	96.8	3.2	-
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	2.74E+1	1	1.59	(3,1,3,1,1,5); Literature 1997, basic uncertainty = 1.5	96.8	3.2	-
waste	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	1.24E-3	1	1.69	(4,4,4,3,4,5); Hagedorn 1992	72.0	2.4	25.6
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,1,1,1,3,3); Estimation	72.0	2.4	25.6
emission air, high population density	Heat, waste	-	-	MJ	2.74E+2	1	3.05	(1,2,1,1,3,3); Calculation with electricity use minus 180 MJ per kg produced silicon	96.8	3.2	-
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	8.81E-6	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	BOD5, Biological Oxygen Demand	-	-	kg	1.43E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	COD, Chemical Oxygen Demand	-	-	kg	1.41E-3	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Chloride	-	-	kg	2.51E-2	1	3.05	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Copper, ion	-	-	kg	7.15E-8	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Nitrogen	-	-	kg	1.45E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Phosphate	-	-	kg	1.96E-6	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Sodium, ion	-	-	kg	2.36E-2	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Zinc, ion	-	-	kg	1.37E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	Iron, ion	-	-	kg	3.92E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
	DOC, Dissolved Organic Carbon	-	-	kg	6.35E-4	1	1.58	(3,na,na,3,1,5); Extrapolation for sum parameter	96.8	3.2	-
	TOC, Total Organic Carbon	-	-	kg	6.35E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product	96.8	3.2	-
price		GLO		€	70.36				75.00	20.00	15.00
revenue		GLO		€	70.36				50.67	1.69	18.00

The unit process raw data of a unit process can be calculated as follows. Multiply the figure in the column „MG-silicon, to ...“ with the allocation factor, divided by 100, divide by the output of product in the three green rows (“allocated products”).

5.3 Solar-grade silicon, modified Siemens process

The production of electronic grade silicon was discussed in the previous section. Most of this material is supplied to the semiconductor industry, and only a small fraction is used for PV wafer production.

To fill the shortage in production capacity for “solar silicon” that has occurred since 2004, a number of EG-silicon producers have started to produce silicon for the solar industry, employing a slightly modified version of the (trichloro)silane/Siemens route which was described above (“modified Siemens”). The most important difference from our perspective is that the energy consumption of the modified Siemens is somewhat lower than in the standard Siemens process, because of the relaxed purity requirements.

Between 12650 and 14400 tonnes of SoG-silicon have been produced in 2005 (Aulich 2006; Rogol 2005). The price of SoG-silicon is about 30 US$ per kg (Hesse & Schindlbeck 2004).

Most of the silicon for photovoltaic applications is presently produced with a modified version of this same process ("modified Siemens" process). The modifications are found in the deposition step and the subsequent crushing and etching processes (see Fig. 5.6).

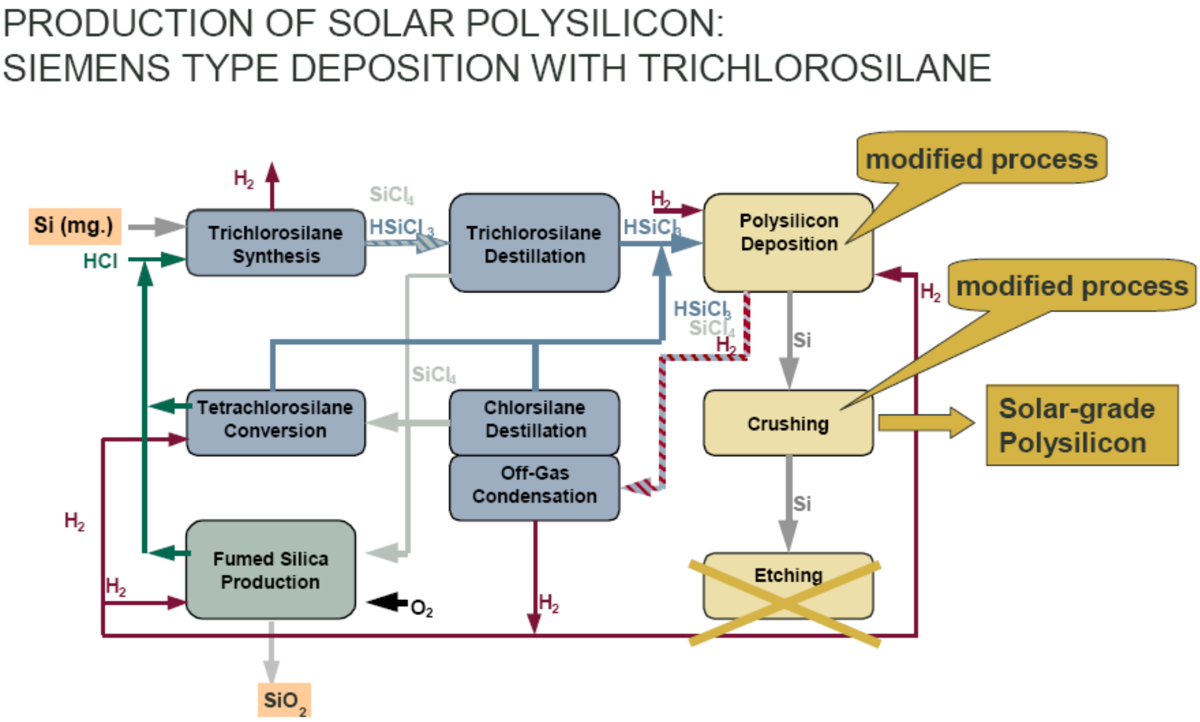


Fig. 5.6 Process scheme for the modified Siemens process for solar-grade polysilicon

The inventory for this process is based on confidential data from one producer that uses a modified Siemens process. For this facility material inputs, thermal input and electricity use are known. In order to protect confidentiality an average of these data with the data given in (Jungbluth 2003, see also chapter 5.2) (50% EG and 50% off-grade) has been made. The electricity consumption of this producer is a bit lower than the figure for Wacker EG-silicon (see chapter 5.2.4). The electricity for this production process is supplied by a nearby hydro power plant and by natural gas cogeneration unit.

The total amount of inorganic chemicals is known with 2 kg of inorganic chemicals per kg of product (de Wild-Scholten & Alsema 2007). The share of different types of specific chemicals has been estimated based on the consumption figures for EG-silicon.

The heat consumption of the process is comparable with the Wacker EG value. For the heat supply a natural gas cogeneration unit, the same as for Wacker, has been assumed.

Direct process emissions to air are not expected. Direct emissions to water are not known. They are estimated with the figures used in the inventory for MG-silicon purification after allocation to the product EG-silicon (see Tab. 5.5, Wacker 2002).

According to the authors of this study, the quality of data for poly-silicon production is not ideal, especially in view of the importance of this process. But, at least reliable data from one manufacturer could be used. It is extremely difficult to get data from this industry type. On the other hand the most important values for this process are those for energy consumption and these matched fairly well between Wacker and the second company. Also the input of MG-silicon matched reasonably. These two producers together have about 30% of the world market for multicrystalline silicon, so that seems fairly representative.[13]

Tab. 5.6 shows the unit process raw data of this process. The meta information for this unit process is shown in Tab. 5.14.

Tab. 5.6 Unit process raw data for solar-grade silicon from the modified Siemens process, feedstock material for "solar wafers" (de Wild-Scholten & Alsema 2007)

	Name	Location	InfrastructureProcess	Unit	silicon, solar grade, modified Siemens process, at plant	Uncertainty	StandardDeviation95	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	silicon, solar grade, modified Siemens process, at plant	RER	0	kg	1.00E+0			
technosphere	MG-silicon, at plant	NO	0	kg	1.13E+0	1	1.10	(2,3,1,2,1,3); Literature
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	1.60E+0	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	hydrogen, liquid, at plant	RER	0	kg	5.01E-2	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	3.48E-1	1	1.14	(3,3,1,2,1,3); de Wild 2007, share of NaOH, HCl and H2 estimated with EG-Si data
	transport, lorry >16t, fleet average	RER	0	tkm	2.66E+0	1	2.09	(4,5,na,na,na,na); Distance 2000km plus 100 km for chemicals
	transport, freight, rail	RER	0	tkm	2.40E+0	1	2.09	(4,5,na,na,na,na); 600km for chemicals including solvent
	electricity, at cogen 1MWe lean burn, allocation exergy	RER	0	kWh	4.50E+1	1	1.10	(2,3,1,2,1,3); literature, actual sources of electricity can vary with considered production location
	electricity, hydropower, at run-of-river power plant	RER	0	kWh	6.50E+1	1	1.10	(2,3,1,2,1,3); literature, actual sources of electricity can vary with considered production location
	heat, at cogen 1MWe lean burn, allocation exergy	RER	0	MJ	1.85E+2	1	1.10	(2,3,1,2,1,3); literature, for process heat
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,3,1,2,3,3); Estimation
emission air	Heat, waste	-	-	MJ	3.96E+2	1	1.10	(2,3,1,2,1,3); Calculation
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	1.26E-5	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	BOD5, Biological Oxygen Demand	-	-	kg	2.05E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	COD, Chemical Oxygen Demand	-	-	kg	2.02E-3	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Chloride	-	-	kg	3.60E-2	1	3.05	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Copper, ion	-	-	kg	1.02E-7	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Nitrogen	-	-	kg	2.08E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Phosphate	-	-	kg	2.80E-6	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Sodium, ion	-	-	kg	3.38E-2	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Zinc, ion	-	-	kg	1.96E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	Iron, ion	-	-	kg	5.61E-6	1	5.06	(1,2,1,1,3,3); Environmental report 2002, average Si product
	DOC, Dissolved Organic Carbon	-	-	kg	9.10E-4	1	1.58	(3,na,na,3,1,5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	9.10E-4	1	1.56	(1,2,1,1,3,3); Environmental report 2002, average Si product

5.4 New solar grade silicon processes (new SoG-silicon)

Since more than 20 years there are research works for the production of so called solar-grade silicon (SoG, *solar grade*, < 10^{-3} Atom-% active impurities). This is tailored for the quality demand of the photovoltaic industry (Pizzini 1982).

The possible production routes for SoG-silicon have been discussed in several literature sources. The direct electricity consumption reported in literature for different types of planned process routes ranged from 15 to 90 kWh/kg.

Tsuo *et al.* (1998) described a chlorine-free process. Ethanol is used instead of trichlorosilane. The electricity use is estimated with 15-30 kWh/kg mc-silicon. But, the yield is estimated with only 6%-20% of the used MG-Si.

Kawasaki Steel Corp. in Japan had first experiences with a process using water vapour. The energy use is estimated with 25 kWh/kg without further information about the type of energy carriers used.[14]

A direct process route for the production of SoG-Si directly from silica sand is described by (Strebkov 1999). He estimated an electricity use of 90 kWh per kg SoG-mc-Si and a yield of 80-90%.

The process planned by Bayer Solar is described by (Pehnt et al. 2002). The electricity use is estimated to be 17 kWh per kg SoG–Si. The silicon losses are high and the yield MG-Si to wafers is estimated with 34%. The company decided to stop further development on this process in 2002 (Woditsch & Koch 2002).

Another process route is developed by Elkem in Norway. The process involves pyro- and hydrometallurgical processes. The metallurgical refining of MG-Si to SoG-Si is estimated to use 25-30 kWh/kg

[13] Personal communication, Erik Alsema, 24.11.2006.

[14] Personal communication, Dr. Fukuo Aratani, Solar Energy Dept., NEDO, JP, 11.2002.

product (Friestad et al. 2006). The production plant is presently under construction and should achieve a production capacity of about 5000 tonnes per year in 2008.

The most successful new process appears to be the application of Fluidized Bed Reactor (FBR) technology for the deposition of silicon from chlorosilane or silane (see Fig. 5.7). At least two manufacturers have set up pilot-scale plants and announced to go to commercial-scale operation in 2007 with FBR technology. It is expected that the electricity consumption of the FBR deposition process will be significantly lower than for Siemens process. de Wild-Scholten & Alsema estimate that the electricity consumption will be 70% lower than for Siemens, in the order of 30 kWh/kg (de Wild-Scholten & Alsema 2005), but no data is given for possible other energy sources and/or for auxiliary supplies.

We will call this material "solar-grade silicon, FBR" to distinguish it from other solar-grade materials. However, as the production for the reference year 2006 was negligible, no unit process raw data are investigated for the type of material.

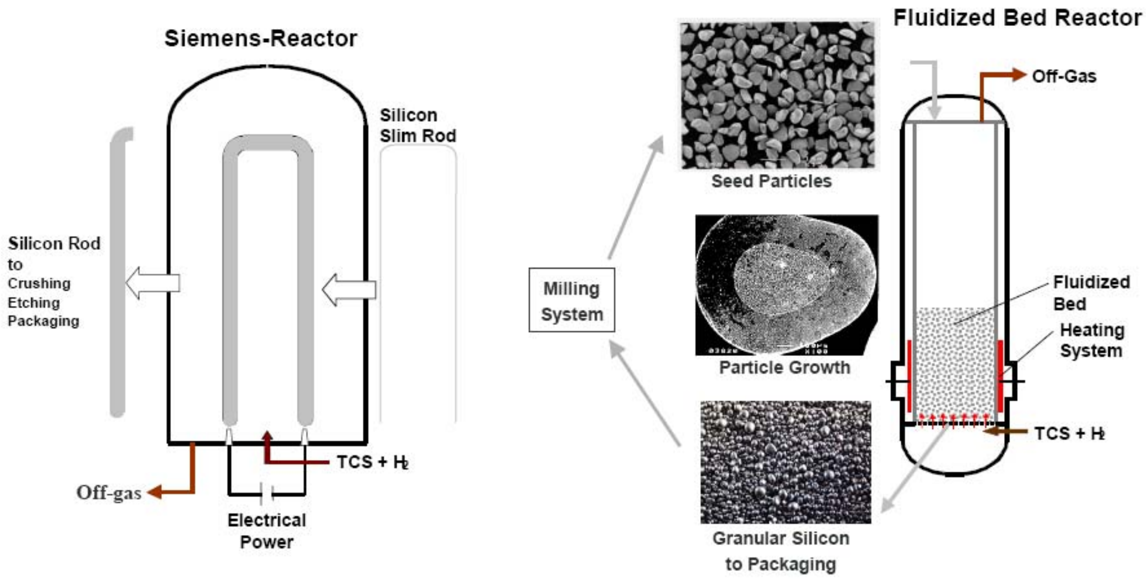


Fig. 5.7 Production of new solar grade silicon processes in fluidized bed reactor

5.5 Production mix for purified silicon used in photovoltaics

The recent years showed a rapid change of silicon qualities used for the production of photovoltaic wafers. In 2005 about 80% of purified silicon feedstock for photovoltaics were produced in processes specifically designed for the purpose of photovoltaic feedstock production. The rest of inputs are based on off-grade silicon and EG-silicon raw materials and wafers (Rogol 2005).

The majority of silicon used in the PV industry nowadays is made specifically for this industry with a modified Siemens process. Off-grade silicon has a decreasing share in PV silicon supply, for 2006 it is estimated at only 5% of total PV supply (Bernreuter 2006). In the future it will decrease further. Solar-grade silicon that is produced with alternative deposition processes like fluidised bed reactor does not have a significant market share yet. This will change in the next few years.[15]

The unit process raw data of the used silicon mix in 2005 are shown in Tab. 5.7. The meta information

[15] Personal communication with Erik Alsema, 24.11.2006.

for this unit process is shown in Tab. 5.14. The global production mix is only represented partly as it was not possible to include all existing production routes and production location in the assessment.

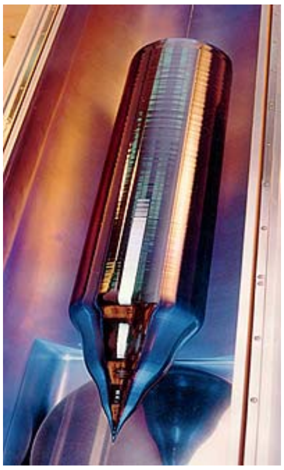
Tab. 5.7 Unit process raw data of the silicon mix used for photovoltaics (Rogol 2005)

	Name	Location	InfrastructureProcess	Unit	silicon, production mix, photovoltaics, at plant	Uncertainty	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				0			
	Unit				kg			
product	silicon, production mix, photovoltaics, at plant	GLO	0	kg	1.00E+0			
	silicon, electronic grade, at plant	DE	0	kg	14.6%	1	1.11	(3,1,1,1,1,1); Literature
	silicon, electronic grade, off-grade, at plant	DE	0	kg	5.2%	1	1.11	(3,1,1,1,1,1); Literature
	silicon, solar grade, modified Siemens process, at plant	RER	0	kg	80.2%	1	1.11	(3,1,1,1,1,1); Literature

5.6 Czochralski singlecrystalline silicon (CZ-sc-Silicon)

Czochralski (CZ) crystals, as shown in Fig. 5.8, can be grown from a wide variety of differently shaped and doped feedstock material. Here we investigate the production for the use in electronics and in photovoltaics. The EG-silicon is molten and a growing crystal is slowly extracted from the melting-pot. The inventory data is based on literature information and environmental reports of one producer in Germany, because other primary information was not available. The product is Czochralski single-crystalline silicon (CZ-sc-Silicon). Information about some German producers of CZ-silicon is shown in Tab. 5.8.

Fig. 5.8 Czochralski monocrystalline silicon crystal. Source: Kayex, U.S.A.



Tab. 5.8 CZ-sc-Silicon producers in the year 2000

Company	Production	Process
	t	
Wacker Siltronic AG, Werk Freiberg, DE	290	Production from EG-silicon, mainly for electronics industry (Wacker 2000)
PV-Silicon, Erfurt, DE	200	Use of Off-Grade silicon, specialized for the demand of the PV-industry (PV Silicon 2002)

5.6.1 Overview

The following description of the production process is based on an older literature reference (Hagedorn & Hellriegel 1992) and has not been updated for this study. The life cycle inventory is based as far as possible on more recent information.

The purified silicon and recycled silicon parts are broken down to a size of 0.1 to 7.5 cm. In an acid bath with nitric acid, hydrogen fluoride and acetic acid the surface is purified and SiO_2 is removed. The following reactions take place:

$$3\ Si + 4\ HNO_3 \rightarrow 3\ SiO_2 + 4\ NO + 2\ H_2O$$

and $$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2\ H_2O$$

The waste gases of the process (e.g. NOx, HF, acetic acid- and nitric acid) are treated in a gas cleaner before they are released. Information about possible releases is not available. Effluents are discharged directly and have been assessed with older literature data. Deionised water is used for cleaning and acetone is used for final drying.

The cleaned silicon parts are melted in a crucible and a seed crystal is first dipped into the melt. Then the seed is slowly withdrawn vertically to the melt surface whereby the liquid crystallises at the seed. The pulling is done under argon inert gas stream. In order to reduce the argon consumption a pressure of 5 to 50 mbar is required.

5.6.2 Energy use

Different figures for the energy use during CZ-Si production from mc-Si are shown in Tab. 5.9 from the literature.

Data for electricity consumption range between 48 and 670 kWh/kg. For this study about 85.6 and 200 kWh/kg have been assumed for CZ-Si used in photovoltaics and electronics, respectively. The assumption is based on information provided by the company Wacker Siltronic in Germany and literature data (de Wild-Scholten & Alsema 2007; Wacker 2006). The data for photovoltaic CZ-ingots are considerably lower than for electronic ingots because the former require less processing and probably because they allow a higher throughput. Further details about reasons for possible differences are not available. The UCTE production mix has been used to model the electricity supply, because this process takes place in different European countries and detailed data for the electricity supply for different producers were not available.

Also the data for the process yield (CZ-silicon output in relation to silicon input) are quite different (see Tab. 5.9). Part of the silicon wastes can be used again as off-grade silicon (see Fig. 5.4). This amount is not considered as a loss as far as it can be directly used as an input to the process. The material efficiency is estimated with the latest literature figures as shown in Tab. 5.9.

Tab. 5.9 Electricity- and silicon use for the production of CZ-Si from mc-Si

Electricity	Efficiency	Electricity	Heat	Source
kWh/kg mc-Si	**%**	**kWh/kg CZ-sc-Si**	**MJ/ kg CZ-sc-Si**	
		100		(Alsema et al. 1998), only second crystallization stage
		390		(Hagedorn & Hellriegel 1992), incl. wafer production
	50%	250		(Williams et al. 2002), older literature from 1996. 20% of wastes can be used for PV.
	80-85%	240-320		(Kato et al. 1997a)
	60%	48.1		(Nijs et al. 1997)
	100%	106.8		Scenario for reduced energy use (Frankl 1998)
117				(Knapp & Jester 2000b)
		140-670		(Alsema et al. 1998)
		50		(Anderson et al. 2002) Only growing from CZ-rods
	70%	127	230	Personal communication for Wacker, electricity use incl. wafer production in 2000 (Wacker 2000)
		200	**270**	(Wacker 2006) for electronics
	93.5%	(100)	**68**	(de Wild-Scholten & Alsema 2007) for PV including wafer sawing
	93.5% (70%)	**85.6 (200)**	**68 (270)**	**This study: photovoltaics (electronics)**

* own calculation subtracting use for wafer sawing

5.6.3 Material use

The use of different materials is calculated with information from literature (de Wild-Scholten & Alsema 2007; Hagedorn & Hellriegel 1992; Wacker 2006). Tab. 5.10 shows the amounts.

Tab. 5.10 Material use for CZ-sc-Silicon production. Disaggregated figures from (Hagedorn & Hellriegel 1992:p. 141, de Wild-Scholten & Alsema 2007; Wacker 2006)

Materials	CZ-Silicon	Remarks
	g/kg	
Tap water	94	Wacker 2006
Surface water	2050	Wacker 2006
Cooling water	2330	Wacker 2006
Nitric acid, HNO_3	94.7	Hagedorn & Hellriegel 1992 *)
Hydrogen fluoride, HF	50.7	Hagedorn & Hellriegel 1992 *)
Acetic acid	108	Hagedorn & Hellriegel 1992 *)
Acetone	49	Cleaning and etching after crystal growth (Hagedorn & Hellriegel 1992)
Argon	5790	Protection gas (de Wild-Scholten & Alsema 2007)
Quartz crucible	336	CZ-crystal growing (de Wild-Scholten & Alsema 2007)
NaOH	41.5	Neutralization for gas washing Hagedorn & Hellriegel 1992
Lime, $Ca(OH)_2$	191	Waste water treatment Hagedorn & Hellriegel 1992

Data for the wafer provided by Hagedorn are multiplied with a factor of 0.56 in order to account for reduced thickness and sawing gap. A consumption of 12.04g EG-Si/Wafer is used for the recalculation.

*) It is possible that data for the use of acids are outdated. Recent information was not available

5.6.4 Emissions

Water emissions from the process are estimated with literature data for the use of chemicals (Hagedorn & Hellriegel 1992). This amount is considered to be discharged to water. It is estimated that these emissions are reduced by a factor of 50% based on the information found on the summarized amount provided in an environmental report (Wacker 2000). Nitrogen emissions are taken as 50% of the total amount reported in an environmental report for CZ-production and wafer production. The second half is considered as an emission in the inventory for wafer production (Wacker 2006). Tab. 5.11 shows this estimation.

The amount of possible process emission is not known. Due to the type of process it is not considered to relevant.

5.6.5 Infrastructure

The mass of one crystal grower for CZ-silicon production is provided by (Knapp & Jester 2000b) with 4536 kg steel for the production of 40 kg CZ-sc-Silicon per day over 10 years. Further information was not available.

Data for the infrastructure in the chemical facilities for silicon production are available (Wacker 2002). They are documented it the report on “silicones” (Althaus et al. 2007). The relevant unit process raw data are applied here to describe the infrastructure for CZ-sc-Silicon production in the same facility.

5.6.6 Life cycle inventory of CZ-sc-Silicon production

Tab. 5.11 shows the unit process raw data for the production of CZ-sc-Silicon. Recycled silicon goes through the same crystallisation process again. That is incorporated in the energy and material data. The system boundary of this process is at the factory fence, and all internal recycling is part of the account. Transports of the silicon input are estimated with 1000 km by truck because there are only two producers in Europe. The meta information for this unit process is shown in Tab. 5.14.

Tab. 5.11 Unit process raw data of CZ-sc-Silicon

	Name	Location	InfrastructureProcess	Unit	CZ single crystalline silicon, electronics, at plant	UncertaintyType	StandardDeviation95%	GeneralComment	CZ single crystalline silicon, photovoltaics, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER				RER			
	InfrastructureProcess				0				0			
	Unit				kg				kg			
product	CZ single crystalline silicon, electronics, at plant	RER	0	kg	1.00E+0				0			
	CZ single crystalline silicon, photovoltaics, at plant	RER	0	kg	0				1.00E+0			
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	2.33E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	2.33E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006
	Water, river	-	-	m3	2.05E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	2.05E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	2.00E+2	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	8.56E+1	1	1.24	(1,4,1,2,1,5); de Wild 2007
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	2.70E+2	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	6.82E+1	1	1.24	(1,4,1,2,1,5); de Wild 2007
water	tap water, at user	RER	0	kg	9.41E+1	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	9.41E+1	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006
	silicon, electronic grade, at plant	DE	0	kg	1.43E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	-	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2000
	silicon, production mix, photovoltaics, at plant	GLO	0	kg	-	1	1.24	(1,4,1,2,1,5); Environmental report Wacker 2006	1.07E+0	1	1.24	(1,4,1,2,1,5); de Wild 2007
materials	argon, liquid, at plant	RER	0	kg	5.79E+0	1	1.24	(1,4,1,2,1,5); de Wild 2007, protection gas for crystal growing	5.79E+0	1	1.24	(1,4,1,2,1,5); de Wild 2007, protection gas for crystal growing
	hydrogen fluoride, at plant	GLO	0	kg	5.07E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992	5.07E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992
	nitric acid, 50% in H2O, at plant	RER	0	kg	9.47E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992	9.47E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992
	acetic acid, 98% in H2O, at plant	RER	0	kg	1.08E-1	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992	1.08E-1	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992
	acetone, liquid, at plant	RER	0	kg	4.90E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992	4.90E-2	1	1.36	(3,4,3,3,3,5); For etching, Hagedorn 1992
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	4.15E-2	1	1.36	(3,4,3,3,3,5); waste gas neutralization, Hagedorn 1992	4.15E-2	1	1.36	(3,4,3,3,3,5); waste gas neutralization, Hagedorn 1992
	ceramic tiles, at regional storage	CH	0	kg	3.36E-1	1	1.24	(1,4,1,2,1,5); de Wild 2007, quartz crucible for melting the silicon	3.36E-1	1	1.24	(1,4,1,2,1,5); de Wild 2007, quartz crucible for melting the silicon
	lime, hydrated, packed, at plant	CH	0	kg	1.91E-1	1	1.36	(3,4,3,3,3,5); waste water treatment, Hagedorn 1992	1.91E-1	1	1.36	(3,4,3,3,3,5); waste water treatment, Hagedorn 1992
transport	transport, lorry >16t, fleet average	RER	0	tkm	2.10E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, sand 50km, silicon 1000km	1.74E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, sand 50km, silicon 1000km
	transport, freight, rail	RER	0	tkm	4.00E+0	1	2.09	(4,5,na,na,na,na); Standard distance 600km	4.00E+0	1	2.09	(4,5,na,na,na,na); Standard distance 600km
infrastructure	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	3.64E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker	3.64E+0	1	1.24	(1,4,1,2,1,5); Environmental report Wacker
emission air, high population density	Heat, waste	-	-	MJ	7.20E+2	1	1.25	(3,3,2,3,1,5); Calculation	7.20E+2	1	1.25	(3,3,2,3,1,5); Calculation
emission water, river	Fluoride	-	-	kg	2.37E-3	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3	2.37E-3	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3
	Hydrocarbons, unspecified	-	-	kg	2.28E-2	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3	2.28E-2	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3
	Hydroxide	-	-	kg	7.42E-3	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3	7.42E-3	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% reduction, basic uncertainty = 3
	Acetic acid	-	-	kg	5.40E-2	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% emission, basic uncertainty = 3	5.40E-2	1	3.08	(3,4,3,3,1,5); Hagedorn 1992, 50% emission, basic uncertainty = 3
	BOD5, Biological Oxygen Demand	-	-	kg	1.30E-1	1	3.08	(5,na,1,1,1,na); Extrapolation for sum parameter	1.30E-1	1	3.23	(5,na,1,1,1,na); Extrapolation for sum parameter
	COD, Chemical Oxygen Demand	-	-	kg	1.30E-1	1	3.08	(5,na,1,1,1,na); Extrapolation for sum parameter	1.30E-1	1	3.23	(5,na,1,1,1,na); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	4.05E-2	1	3.08	(5,na,1,1,1,na); Extrapolation for sum parameter	4.05E-2	1	3.23	(5,na,1,1,1,na); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	4.05E-2	1	3.08	(5,na,1,1,1,na); Extrapolation for sum parameter	4.05E-2	1	3.23	(5,na,1,1,1,na); Extrapolation for sum parameter
	Nitrogen	-	-	kg	9.10E-3	1	1.61	(3,4,3,3,1,5); Environmental report Wacker 2006, 50% of total emissions	9.10E-3	1	1.61	(3,4,3,3,1,5); Environmental report Wacker 2006, 50% of total emissions

5.7 Casting mc-silicon

EG-silicon, off-grade silicon and SoG-silicon are molten and casted or melted in(to) crucibles (Fig. 5.9). Fig. 5.10 shows the production process. The purified silicon is casted into a quartz crucible. The crucibles are afterwards reused in road construction. The large round mc-Si blocks are cut with saws to square blocks. The cuttings can be partly reused. Wafers can be directly produced from these multicrystalline blocks.

Data for this production stage are estimated using published information (de Wild-Scholten & Alsema 2007; Nijs et al. 1997). Energy data are reported in Tab. 5.12. Further information about the type of process behind these figures are not available.

Fig. 5.9 400 kg ingot produced in Integrated Project Crystal-Clear. Source: Deutsche Solar, Germany

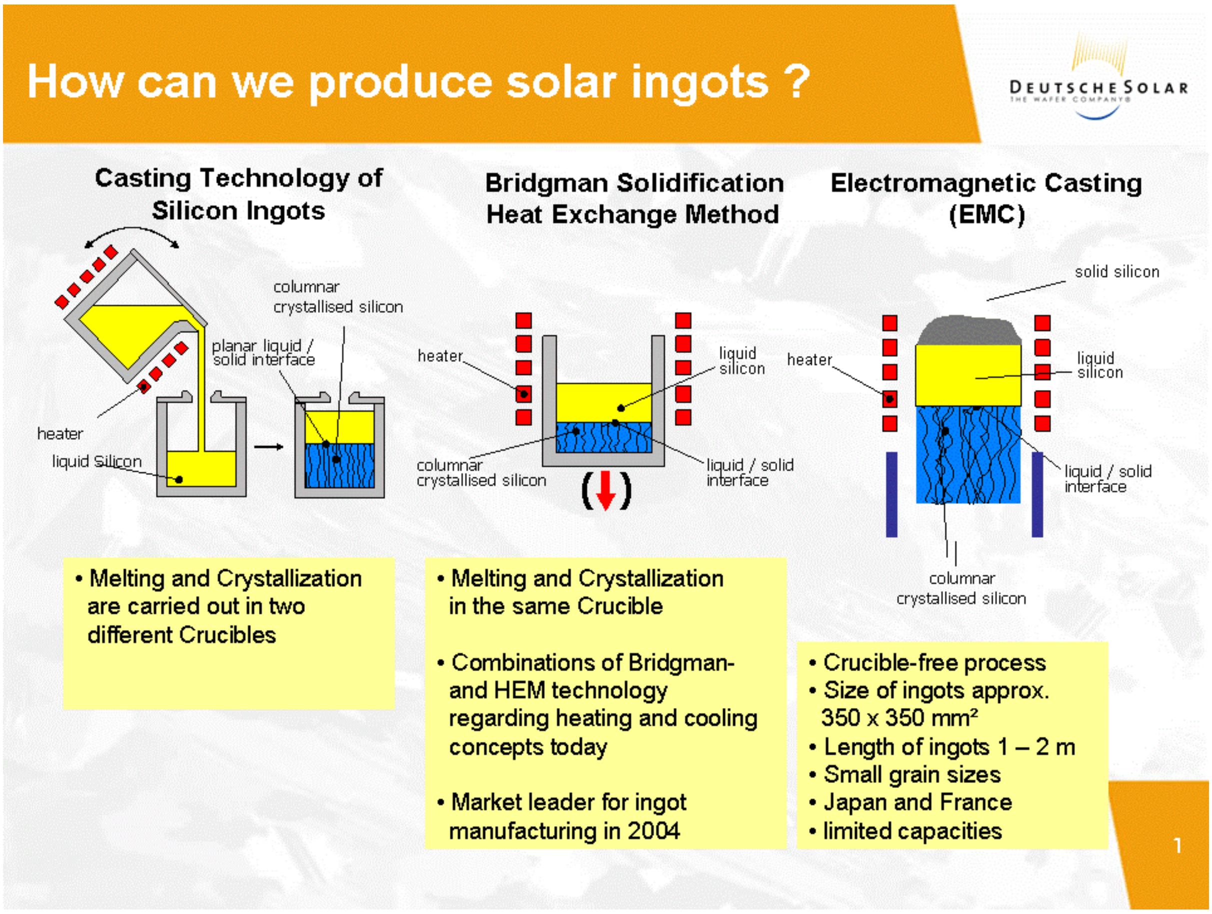


Fig. 5.10 Ingot growing methods. Source: Deutsche Solar, Germany

Tab. 5.12 Energy use for casting of multicrystalline silicon

Efficiency	Electricity	Source
%	kWh/kg mc-Si	
	48	<Strese *et al.* 1988>
64%	20.9	(Nijs et al. 1997)
70%		(Sarti & Einhaus 2002)
88%	*(23)*	including wafer sawing (de Wild-Scholten & Alsema 2007)
88%	**19.3**	**This study,** calculation by (de Wild-Scholten & Alsema 2007) minus electricity use for wafer sawing

Tab. 5.13 shows the unit process raw data of silicon casting. The inventory considers the energy use for melting and some material inputs, but no direct emissions to air and water, because information was not available (de Wild-Scholten & Alsema 2007; Nijs et al. 1997). The transport of purified silicon to this production stage is assumed with 1000 km by truck because there are only 2 producers in Europe. The meta information for this unit process is shown in Tab. 5.14.

Tab. 5.13 Unit process raw data of casting for multicrystalline silicon

	Name	Location	InfrastructureProcess	Unit	silicon, multi-Si, casted, at plant	UncertaintyType	StandardDeviation	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	silicon, multi-Si, casted, at plant	RER	0	kg	1.00E+0			
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	5.00E+0	1	1.26	(3,4,2,3,1,5); Nijs 1997
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.93E+1	1	1.07	(1,2,1,1,1,3); Estimation with de Wild 2007
	argon, liquid, at plant	RER	0	kg	2.67E-1	1	1.07	(1,2,1,1,1,3); de Wild 2007, for ingot growing
	helium, gaseous, at plant	RER	0	kg	1.19E-4	1	1.07	(1,2,1,1,1,3); de Wild 2007, for ingot growing
	nitrogen, liquid, at plant	RER	0	kg	4.67E-2	1	1.07	(1,2,1,1,1,3); de Wild 2007, for ingot growing
	ceramic tiles, at regional storage	CH	0	kg	3.42E-1	1	1.07	(1,2,1,1,1,3); de Wild 2007, quarz for ingot growing
	silicon, production mix, photovoltaics, at plant	GLO	0	kg	1.14E+0	1	1.07	(1,2,1,1,1,3); de Wild 2007, total silicon needed minus internally recycled silicon from ingot cut-offs and broken wafers.
	transport, lorry >16t, fleet average	RER	0	tkm	1.17E+0	1	2.09	(4,5,na,na,na,na); Standard distances 50km, silicon 1000km
	transport, freight, rail	RER	0	tkm	6.56E-2	1	2.09	(4,5,na,na,na,na); Standard distances 100km
	silicone plant	RER	1	unit	1.00E-11	1	3.05	(1,2,1,1,3,3); Estimation
emission air	Heat, waste	-	-	MJ	6.95E+1	1	1.25	(3,3,2,3,1,5); Calculation

5.8 Meta information of crystalline silicon products

Tab. 5.14 shows the EcoSpold meta information of different silicon products investigated in this chapter.

Tab. 5.14 EcoSpold meta information of different silicon products

ReferenceFunction	Name	MG-silicon, to purification	silicon, solar grade, modified Siemens process, at plant	silicon, production mix, photovoltaics, at plant	silicon, multi-Si, casted, at plant	CZ single crystalline silicon, electronics, at plant	CZ single crystalline silicon, photovoltaics, at plant
Geography	Location	DE	RER	GLO	RER	RER	RER
ReferenceFuncti	InfrastructureProcess	0	0	0	0	0	0
ReferenceFuncti	Unit	kg	kg	kg	kg	kg	kg
	IncludedProcesses	Purification of MG-silicon including materials, energy use, wastes and air emissions.	Gate to gate inventory for the production of high purity polycrystalline silicon from MG-silicon in actual processes. Only energy use, chemicals and yield are known. Emissions to water are roughly estimated.	Production mix for the purified silicon feedstock used for sc- and mc-Si cell in photovoltaics. The global production mix is represented partly as it was not possible to include all existing	Gate to gate inventory for the casting of EG-Si and off-grade Si.	Gate to gate inventory for the Czochralski process. Crushing of Si, etching with HNO_3, HF and acetic acid. Melting in a silica pot and crystallisation to produce a monocrystalline material. Water emissions roughly estimated. Process emissions	Gate to gate inventory for an improved Czochralski process. Crushing of Si, etching with HNO_3, HF and acetic acid. Melting in a silica pot and crystallisation to produce a monocrystalline material. Water emissions roughly estimated. Process
	LocalName	MG-Silizium, in Reinigung	Silizium, Solaranwendung, modifizierter Siemens Prozess, ab Werk	Silizium, Produktionsmix, Photovoltaik, ab Werk	Silizium, multi-Si, im Block, ab Werk	CZ single-Silizium, Elektronik, ab Werk	CZ single-Silizium, Photovoltaik, ab Werk
	Synonyms	EG-Si	SoG-Silicon//polycrystaline		polycrystaline	Czochralski process	Czochralski process
	GeneralComment	The multi-output-process "MG-silicon, to purification" delivers the co-products "silicon, electronic grade", "silicon, electronic grade, off-grade", "silicon tetrachloride". The allocation is based on mass balance and economic criteria. World production of EG-Si was 18'000t in 2000, 2'000t were sold as off-grade Si to the photovoltaic industry. Wacker produced 3'000t EG-Si. Total production $SiCl_4$ 1.6 million tonnes from different processes.	Process for silicon used in photovoltaic industry. Purity >98% sufficient for use in photovoltaic industry.	Production mix of different feedstock for silicon used in photovoltaic industry. Purity >98% sufficient for use in photovoltaic industry	Production of a polycrystalline block with a weight of about 250kg.	Production of a monocrystalline block with a diameter of 130mm and a length of 150cm. Losses of non-recycled material due to block cutting are included.	Production of a monocrystalline block with a diameter of 130mm and a length of 150cm. Losses of non-recycled material due to block cutting are included.
	Category	metals	metals	metals	metals	photovoltaic	photovoltaic
	SubCategory	refinement	refinement	refinement	refinement	production of components	production of components
	Formula	Si	Si	Si	Si	Si	Si
	StatisticalClassification						
	CASNumber	7440-21-3	7440-21-3	7440-21-3	7440-21-3	7440-21-3	7440-21-3
TimePeriod	StartDate	1992	2004	2005	1997	1992	1992
	EndDate	2005	2005	2005	2005	2006	2006
	OtherPeriodText	Time of publications.	Time of investigation	Time of investigation	Time of data collection. Data refer to 2005.	Most data are published in 2006. Some older data published in 1992.	Most data are published in 2006. Some older data published in 1992.
Geography	Text	The inventory is modelled for the largest European production plant. For the second plant in IT data were not available.	Data for different types of processes in Europe and North America.	Data for the worldwide consumption.	Estimation for RER.	Data for a plant in DE and estimation for RER.	Data for RER.
Technology	Text	Production of $HSiCl_3$ with HCl, cleaning, vacuum distillation and production of the three products.	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.	Market mix of different technologies.	Purified silicon is melted in cast in a graphite box. Than edges are sliced and blocks are sawn.	Czochralski process for production of monocrystalline silicon blocks. Than edges are sliced and blocks are sawn.	Czochralski process for production of monocrystalline silicon blocks. Than edges are sliced and blocks are sawn.
Representativen	Percent	75	75	90	0	10	10
	ProductionVolume	World production of EG-Si was 17'000t in 2005.	12600 t in 2005	15000 t in 2005	Not known.	16000 tonnes in 2005.	not known
	SamplingProcedure	Literature data.	Average of data from one company and estimated data from another company based on literature data	Literature.	Literature data.	Publication of plant specific (partly aggregated) data.	Publication of plant specific (partly aggregated) data and literature information.
	Extrapolations	Some data are derived from other or unknown plants.	Emissions to water are estimated with figures investigated for MG-silicon purification to EG-silicon with a similar type of process.	none	Extrapolation with cumulative data including wafer sawing for electricity use.	none	none

6 Silicon wafer production

6.1 Production process

6.1.1 sc-Si and mc-Si wafers

The wafer sawing is investigated together for sc-Si and mc-Si wafer as the differences in the production process are considered to be minor. Most of the producers use today a multi-wire slicing technology. This has the advantage of high wafer throughputs per day compared to inner diameter saws.

The silicon ingots are cut in a first step by band saws or wire sawing into columns with a cross section determined by the final wafer size. The columns are placed in a multi-wire saw that slices them into wafers (see Fig. 6.1). A single wire might be several kilometres long. The wires are tightened parallel. Cutting is achieved by abrasive slurry with silicon carbide. The sludge from the sawing is recycled (see chapter 4.4 for the unit process raw data of this process).

New technologies are developed in order to reduce the kerf losses and thus increase the silicon efficiency (Nasch et al. 2006).

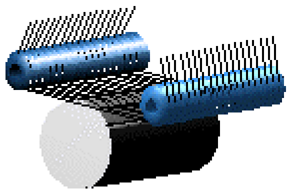


Fig. 6.1 Multi-wire saw (www.tocera.co.kr/en/research/slicej.html)

The wafers are cleaned after the process. Different chemicals might be used for this purpose, e.g. KOH or NaOH, hydrochloric acid, acetic acid, and tenside.

The wafers are then packaged in polystyrene and plastic foil. The amount of these materials was estimated in <Strese *et al.* 1988, p. 24>.

The most important producers of wafers for photovoltaics are shown in Tab. 6.1.

Tab. 6.1 Wafer producers in 2005 (Brand 2006; Ilken 2006; Schmela 2005)

Company	Country	Si-Type	Production (million dm2)
Amex	RU	sc-Si	3.6
Asi Industries	DE		11.3
BP Solar	US	mc-Si	55.6
Deutsche Solar	DE	mc-Si/sc-Si	107
Elma-Phytol	RU	sc-Si	4
Evergreen	US	mc-Si	10.8
Green Energy Technology	TW	mc-Si	15.2
JFE	Asia	mc-Si	13
PCMP	RU	sc-Si	14.5
PV Crystalox, Erfurt	DE	mc-Si	80
ScanWafer	NO	mc-Si	149
Swiss Wafer	CH	sc-Si	12
Schott Solar	DE	mc-Si	27.9
Shunda	Asia	sc-Si	23
M. Setek	JP	sc-Si	71.9

6.1.2 Ribbon silicon wafers

As a third type of wafers we investigate here ribbon silicon wafers. These wafers are also made of multicrystalline silicon. The silicon wafers are not sawn from blocks, but they are directly pulled or casted from liquid silicon. Thus a much higher material efficiency can be achieved because sawing losses are avoided.

A 100-300 µm thick silicon film is produced directly. This is cut to square pieces e.g. with a laser. Important processes are the edge-defined film-fed growth (EFG), string ribbon and ribbon growth on substrate (RGS).

SCHOTT Solar commercially uses the EFG process. The silicon ribbon is pulled to heights of up to 7 m from the top of a graphite die (Hahn & Schönecker 2004). Evergreen Solar Inc uses the string ribbon technology. It uses high temperature resistant strings, which are drawn at a distance of 8 cbetween each other through a crucible with liquid silicon. They pull up a meniscus of about 7 mm height, which crystallizes to become the ribbon (Hahn & Schönecker 2004). For the production of RGS a series of graphite based substrates move at high velocity under a casting frame, which contains liquid silicon and defines the size of the wafers and the solidification front (Hahn & Schönecker 2004).

6.2 Wafer thickness and surface

The material efficiency for the used silicon is quite important. Tab. 6.2 and Tab. 6.3 show the development and literature information about wafer thickness and sawing losses. Technically it is possible to produce wafers with a thickness down to 100µm. But, most of the production plants have a higher thickness in order to ensure a good handling of the wafers with lower losses due to breakages.

The reference flow for the life cycle inventory is one square metre of wafer surface. The sc-silicon columns are sawn into square wafers with a size 156x156 mm^2 (0.0243 m^2) and an assumed thickness of 270 µm. The final wafer weight is 629 g/m^2. The mc-silicon columns are sawn into wafers with a square size 156x156 mm^2 (0.0243 m^2) and an assumed thickness of 240 µm. The weight is 559 g/m^2. The ribbon silicon wafers have a wafer thickness of 200-300 µm. The wafer area is 120 to 156 cm^2, thickness 250 µm. The weight is 583 g/m^2. It is not possible to recycle the silicon kerf loss with current technology (de Wild-Scholten & Alsema 2007).

Tab. 6.2 Literature data for sc-Si wafer thickness and kerf loss

Wafer thickness	Kerf loss	Type of sawing	Year	Source
µm	**µm**			
450	450	ID-saw	1992	(Hagedorn & Hellriegel 1992)
300[1])	200[1])	multi-wire	1996	(Frischknecht et al. 1996)
350	250 [2])	multi-wire	1997	(Kato et al. 1997b)
~315	190	Plus 10-20µm losses for ends and edges. Larger wafer must be thicker for stability reasons.	1999	(Knapp & Jester 2000b) and E-Mail-communication with Karl E. Knapp, Energy and Environmental Economics, USA, 19.10.2000.
125	n.d.	wire-saw, research status	2003	(www.nrel.gov/pvmat/siemens5.html)
200	n.d.	Wire saw	2003	(www.nrel.gov/pvmat/siemens5.html).
280-370	n.d.	sc-Si solar cells	2003	(www.eurosolare.it, Italy).
350-400	n.d.	Russian production	2003	Viva solar Inc., Canada (www.vivasolar.com/pseudosquare.html)
200-700	ID-saw 300, wire saw 180	wafer electronics	2003	Wacker Siltronic AG, Freiberg.
300	200	Estimation	2003	(Jungbluth 2003)
270	**190**	**calculated with losses that cannot be recycled**	**2005**	**This study (de Wild-Scholten & Alsema 2007)**

n.d. no data

[1]): Estimation

[2]): Calculated with data for the silicon yield (50 to 60%).

Tab. 6.3 Literature data for mc-Si wafer thickness and kerf loss

Wafer thickness	Kerf loss	Type of sawing	Year	Source
µm	**µm**			
150[1]), 200, 300[1])	150[1]), 200, 300[1])	best/base/worst case	1995	(Phylipsen & Alsema 1995)
200[1])	200[1])	Capacity 100MW	1997	(Kato 1999; 2000)
250	200	Capacity 10MW	1997	(Kato 1999; 2000)
300[1])	200[1])	multi-wire	1996	(Frischknecht et al. 1996)
350		multi-wire	1992	(Hagedorn & Hellriegel 1992)
380	180	Plus 10-20µm losses for ends and edges. Larger wafer must be thicker for stability reasons.	1999	(Knapp & Jester 2000b) and E-Mail-communication with Karl E. Knapp, Energy and Environmental Economics, USA, 19.10.2000.
280-370	n.d.		2003	(www.eurosolare.it, IT)
300	n.d.		2003	Shell solar Deutschland Homepage
330-360	n.d.	multi-blade wire saws	2003	(www.scanwafer.com, Norway).
300	200	Estimation	2003	(Jungbluth 2003)
240	**250**	**calculated with losses and material use**	**2005**	**This study (de Wild-Scholten & Alsema 2007)**
	200	expert guess	2005	Personal communication E. Alsema, 6.2007
200	180-190		1.2007	Personal communication de Wild for new average data

n.d. no data

[1]): Estimation

6.3 Energy use and silicon consumption

Tab. 6.4 shows the information for the electricity use for wafer sawing as reported in different studies. Some studies collected data for different stages lumped together. For this study we assume an electricity use of 8 kWh/m^2 for photovoltaics wafer and 30 kWh/m^2 for electronics wafer. The most recent data have been used for photovoltaic wafers. The reliable information for today production, which includes wafering and casting, is used as the basis for the assumption. It has been disaggregated between the two process stages (see also Tab. 5.12). A part of the variation of the data on electricity use might also be explained by different wafer thickness and sawing gaps. But, it was not possible to include such differences to account for differences in wafer thickness between single- and multi-silicon wafers.

The difference between figures for wafers used in electronics and photovoltaics cannot be explained with the available information, but partly with the different age of data and possible variations between different factories. No further investigations have been made because of the low importance in the overall inventory. Differences between sc-Si and mc-Si wafers could not be investigated. They are assumed to be less relevant than differences between different production facilities.

The consumption of natural gas for removing adhesive after sawing is 4 MJ/m^2 (de Wild-Scholten & Alsema 2007).

The material efficiency calculation is also based on a recent survey for different producers (de Wild-Scholten & Alsema 2007).

Tab. 6.4 Electricity use for the production of wafers from silicon. Figures in brackets summarize more than one process stage. Recalculated for a wafer size of 100 cm^2.

Electricity	Electricity	Efficiency	Source
kWh/kg	kWh/Wafer	%	
	(2.2)		(Hagedorn & Hellriegel 1992) , incl. CZ-Silicon production
	(1.7)		(Hagedorn & Hellriegel 1992), incl. mc-casting
(210)	(1.47)		(Kato et al. 1997b), incl. CZ-Si production
	0.125	60.5%	(Nijs et al. 1997)
	0.2-0.7		(Frankl & Gamberale 1998)
	0.24		(Alsema 2000a)
-	-	66%	(Sarti & Einhaus 2002)
240	1.68	56%	(Williams et al. 2002) for sc-Si wafe*r
	(9)		Wacker 2000, Total incl. CZ-Si production
	0.3	66%	(Jungbluth 2003) calculated with Wacker data for electronics
	(0.3)	59%/47%	Including casting (de Wild-Scholten & Alsema 2007) for sc-Si/mc-Si
	0.06-0.1		Estimation[16]
	0.08 (0.3)	**59%/47%**	**This study,** efficiency for sc-Si/mc-Si (estimation electronics wafer). Considered also for the disaggregation of the data used for casting (see Tab. 5.12).

6.4 Materials

Tab. 6.5 shows the inputs and auxiliary materials used for the wafer sawing. The data investigated in the CrystalClear project have been used as far as available (de Wild-Scholten & Alsema 2007). The estimation for argon in the process for electronics wafer is based on Phylipsen & Alsema (1995). Further information were available for the company Wacker (Wacker 2000; 2006; personal communica-

[16] Personal communication with Erik Alsema, 9.3.2007.

tion[17]). The assumption for the use of glass is based on literature data (Nijs et al. 1997).

6.5 Output, Emissions

Wafers are cleaned after sawing. Therefore acids are applied, e.g. HF, HCl or acetic acid. Emissions from this process are feed to a gas-cleaning unit and they are neutralized with sodium hydroxide. The amount of other air emissions is not known.

The effluent contains e.g. sodium nitrate, sodium fluoride or sodium acetate. The effluents are feed to an internal wastewater treatment plant. Most of the data have been investigated for different production plants in 2005 (de Wild-Scholten & Alsema 2007). Some data are derived from an environmental report of the company Siltronic AG (Wacker 2000; 2006).

The wafers produced for the electronic industry receive a surface-polishing step to make nice shiny wafers. The quality standards for micro-electronic wafers are much higher and more post-sawing processing is applied. Polishing is done in the electronics industry with nitric acid. Because, the PV industry needs rough wafers, this polishing step is not done here[18]. Therefore no NO_x emission will occur in the PV wafer production from the use of nitric acid.

6.6 Life cycle inventory of silicon wafer production

Tab. 6.5 shows the unit process raw data for silicon wafers. Recent literature data have been used to elaborate this life cycle inventory (de Wild-Scholten & Alsema 2007; Kato et al. 1998; Nijs et al. 1997; Phylipsen & Alsema 1995; Wacker 2000; 2006). The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific NOx- and waterborne pollutants are considered based on information from literature and environmental reports. Emissions of NO_x due to surface etching with HNO_3 are important for the electronics wafers where these etching agents are used. Producers for PV-wafers apply normally technologies with etching agents like NaOH or KOH, or dry etching. The later is included in solar cell processing data). The same data have been used for sc-Si and mc-Si wafer production, because the full information for sc-Si wafer was not available.

17 Personal communication D. Rössler, Wacker Siltronic AG, Werk Freiberg, 12.2002

18 Use of nitric acid for texturing wafers is included in the solar cell processing data, the NOx emissions occurring here are generally abated at the plant level (Personal communication with Erik Alsema and Mariska de Wild-Scholten, 24.11.2006)

Tab. 6.5 Unit process raw data of wafer production including wafer sawing

	Name	Location	Infrastructure	Unit	single-Si wafer, photovoltaics, at plant	single-Si wafer, electronics, at plant	multi-Si wafer, at plant	multi-Si wafer, ribbon, at plant	StandardDeviation95	GeneralComment
	Location				RER	RER	RER	RER		
	InfrastructureProcess				0	0	0	0		
	Unit				m2	m2	m2	m2		
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	8.00E+0	3.00E+1	8.00E+0	4.23E+1	2.07	(3,4,1,3,1,5); Estimation based on literature data, high range of literature values
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	4.00E+0	4.00E+0	4.00E+0	-	1.07	(1,2,1,1,1,3); de Wild 2007, for removing adhesive after sawing
water	tap water, at user	RER	0	kg	6.00E-3	6.85E+2	6.00E-3	-	1.07	(1,2,1,1,1,3); de Wild 2007
	water, completely softened, at plant	RER	0	kg	6.50E+1	-	6.50E+1	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
material	CZ single crystalline silicon, electronics, at plant	RER	0	kg	-	1.07E+0	-	-	1.07	(1,2,1,1,1,3);
	CZ single crystalline silicon, photovoltaics, at plant	RER	0	kg	1.07E+0	-	-	-	1.07	(1,2,1,1,1,3); Own calculation with de Wild 2007 data
	silicon, multi-Si, casted, at plant	RER	0	kg	-	-	1.14E+0	-	1.07	(1,2,1,1,1,3); polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from ingot cut offs and broken wafers.
	silicon, production mix, photovoltaics, at plant	GLO	0	kg	-	-	-	7.40E-1	1.07	(1,2,1,1,1,3); polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon broken
	silicon carbide, at plant	RER	0	kg	4.90E-1	4.90E-1	4.90E-1	-	1.07	(1,2,1,1,1,3); de Wild 2007, SiC use for sawing
	silicon carbide, recycling, at plant	RER	0	kg	2.14E+0	2.14E+0	2.14E+0	-	1.07	(1,2,1,1,1,3); de Wild 2007, SiC use for sawing
auxiliary material	graphite, at plant	RER	0	kg	-	-	-	6.60E-3	1.07	(1,2,1,1,1,3); de Wild 2007, graphite
	argon, liquid, at plant	RER	0	kg	-	5.75E-1	-	5.21E+0	1.26	(3,4,2,3,1,5); Protection gas sawing, de Wild 2007
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.50E-2	1.50E-2	1.50E-2	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	2.70E-3	2.70E-3	2.70E-3	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
	acetic acid, 98% in H2O, at plant	RER	0	kg	3.90E-2	3.90E-2	3.90E-2	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
	nitric acid, 50% in H2O, at plant	RER	0	kg	-	3.70E-1	-	-	1.58	(5,4,1,3,1,5); calculated with NOx emissions, Wacker 2006
	triethylene glycol, at plant	RER	0	kg	1.10E-1	1.10E-1	1.10E-1	-	1.07	(1,2,1,1,1,3); For sawing slurry, de Wild 2007
	triethylene glycol, recycling, at plant	RER	0	kg	2.60E+0	2.60E+0	2.60E+0	-	1.07	(1,2,1,1,1,3); For sawing slurry, de Wild 2007
	dipropylene glycol monomethyl ether, at plant	RER	0	kg	3.00E-1	3.00E-1	3.00E-1	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
	alkylbenzene sulfonate, linear, petrochemical, at plant	RER	0	kg	2.40E-1	2.40E-1	2.40E-1	-	1.07	(1,2,1,1,1,3); de Wild 2007, for wafer cleaning
	acrylic binder, 34% in H2O, at plant	RER	0	kg	2.00E-3	2.00E-3	2.00E-3	-	1.07	(1,2,1,1,1,3); de Wild 2007, adhesive for temporarily attachment of bricks to wire-sawing equipment
	glass wool mat, at plant	CH	0	kg	1.00E-2	1.00E-2	1.00E-2	-	1.07	(2,2,1,1,1,na); de Wild 2007, for temporarily attachment of bricks to wire sawing equipment
	paper, woodfree, coated, at integrated mill	RER	0	kg	1.90E-1	1.90E-1	1.90E-1	1.90E-1	1.29	(3,4,3,3,1,5); Hagedorn 1992
	polystyrene, high impact, HIPS, at plant	RER	0	kg	2.00E-1	2.00E-1	2.00E-1	2.00E-1	1.34	(4,4,3,3,1,5); estimation packaging
	packaging film, LDPE, at plant	RER	0	kg	1.00E-1	1.00E-1	1.00E-1	1.00E-1	1.34	(4,4,3,3,1,5); estimation packaging
	brass, at plant	CH	0	kg	7.45E-3	7.45E-3	7.45E-3	-	1.07	(1,2,1,1,1,3); de Wild 2007, wire saws, high resistance brass-coated steel with carbon content in the range 0.7%-0.9%, 5g/kg brass
	steel, low-alloyed, at plant	RER	0	kg	1.48E+0	1.48E+0	1.48E+0	-	1.07	(1,2,1,1,1,3); de Wild 2007, wire saws, high resistance brass-coated steel with carbon content in the range 0.7%-0.9%, 5g/kg brass
	wire drawing, steel	RER	0	kg	1.49E+0	1.49E+0	1.49E+0	-	1.07	(1,2,1,1,1,3); de Wild 2007, wire saws
wastes	disposal, waste, silicon wafer production, 0% water, to underground deposit	DE	0	kg	1.10E-1	6.17E-2	1.70E-1	7.00E-3	1.07	(1,2,1,1,1,3); de Wild 2007, estimate for unused parts of crystal
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	-	1.71E+0	-	-	1.24	(2,4,1,3,1,5); Environmental report Wacker
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	-	7.26E+0	-	-	1.24	(2,4,1,3,1,5); Environmental report Wacker
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.06E+0	1.55E+0	1.10E+0	3.14E-1	2.09	(4,5,na,na,na,na); Standard distance, 200km for silicon input
	transport, freight, rail	RER	0	tkm	4.13E+0	4.41E+0	4.13E+0	8.19E-1	2.09	(4,5,na,na,na,na); Standard distance
infrastructure	wafer factory	DE	1	unit	4.00E-6	4.00E-6	4.00E-6	4.00E-6	3.00	(1,2,1,1,1,3); Literature
emission air	Heat, waste	-	-	MJ	2.88E+1	1.08E+2	2.88E+1	1.52E+2	1.26	(3,4,1,3,1,5); Calculation
	Nitrogen oxides	-	-	kg	-	3.70E-1	-	-	1.58	(2,4,1,3,1,5); Environmental report Wacker 2006
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	5.01E-4	5.01E-4	5.01E-4	5.01E-4	1.58	(2,4,1,3,1,5); Environmental report Wacker 2006, formed by nitric acid use
	Cadmium, ion	-	-	kg	6.05E-6	6.05E-6	6.05E-6	6.05E-6	3.06	(2,4,2,3,1,5); Environmental report Wacker 2000
	Chromium, ion	-	-	kg	3.03E-5	3.03E-5	3.03E-5	3.03E-5	3.06	(2,4,2,3,1,5); Environmental report Wacker 2000
	COD, Chemical Oxygen Demand	-	-	kg	2.96E-2	2.96E-2	2.96E-2	2.96E-2	1.58	(2,4,1,3,1,5); Environmental report Wacker 2000
	Copper, ion	-	-	kg	6.05E-5	6.05E-5	6.05E-5	6.05E-5	3.06	(2,4,2,3,1,5); Environmental report Wacker 2000
	Lead	-	-	kg	3.03E-5	3.03E-5	3.03E-5	3.03E-5	5.07	(2,4,2,3,1,5); Environmental report Wacker 2000
	Mercury	-	-	kg	6.05E-6	6.05E-6	6.05E-6	6.05E-6	5.07	(2,4,2,3,1,5); Environmental report Wacker 2000
	Nickel, ion	-	-	kg	6.05E-5	6.05E-5	6.05E-5	6.05E-5	5.07	(2,4,2,3,1,5); Environmental report Wacker 2000
	Nitrogen	-	-	kg	9.94E-3	9.94E-3	9.94E-3	9.94E-3	1.58	(2,4,1,3,1,5); Environmental report Wacker 2006, 50% of total emissions
	Phosphate	-	-	kg	5.01E-4	5.01E-4	5.01E-4	5.01E-4	1.58	(2,4,1,3,1,5); Environmental report Wacker 2006
	BOD5, Biological Oxygen Demand	-	-	kg	2.96E-2	2.96E-2	2.96E-2	2.96E-2	1.59	(3,4,2,3,1,5); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1.59	(3,4,2,3,1,5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	1.11E-2	1.11E-2	1.11E-2	1.11E-2	1.59	(3,4,2,3,1,5); Extrapolation for sum parameter

6.7 Infrastructure

The infrastructure for the production of wafers has been investigated with data from different companies (de Wild-Scholten & Alsema 2007; Wacker 2002). Data of Wacker were available for two production places. But, for the Wasserburg plant the data of the produced amount had to be assessed roughly. Data for Freiberg have been divided by two to account for the parallel production of CZ-silicon. Tab. 6.6 shows the unit process raw data.

Tab. 6.6 Unit process raw data of the infrastructure for wafer manufacturing with a capacity of 1 Mio. wafer per year, lifetime 25 years

	Name	Location	Infra	Unit	wafer factory	Uncertainty	StandardDeviation	GeneralComment	*Wacker Wasserburg*	*Wacker Freiberg*	*de Wild 2007*
	Location				DE				*DE*	*DE*	*RER*
	InfrastructureProcess				1				*0*	*0*	
	Unit				unit				*a*	*a*	*a*
product	wafer factory	DE	1	unit	1.00E+0						
technosphere	building, hall	CH	1	m2	1.10E+2	1	3.00	(1,2,1,1,1,3); Environmental report	1.00E+4	-	2.40E+3
	water supply network	CH	1	km	2.19E-2	1	3.00	(1,2,1,1,1,3); Environmental report, pipelines for drinking water	2.00E+0		
	metal working machine, unspecified, at plant	RER	1	kg	1.00E+4	1	3.91	(5,3,1,1,5,3); Rough estimation for equipment			
resource, land	Occupation, industrial area	-	-	m2a	2.74E+3	1	2.00	(1,2,1,1,1,3); 25a occupation		-	
	Transformation, from unknown	-	-	m2	7.68E+2	1	2.00	(1,2,1,1,1,3); Environmental report	7.00E+4	8.25E+4	2.40E+3
	Transformation, to industrial area, built up	-	-	m2	1.10E+2	1	2.00	(1,2,1,1,1,3); Environmental report	1.00E+4		2.40E+3
	Transformation, to industrial area, vegetation	-	-	m2	3.29E+2	1	2.00	(1,2,1,1,1,3); share of area according to environmental report	3.00E+4		
	Transformation, to traffic area, road network	-	-	m2	3.29E+2	1	2.00	(1,2,1,1,1,3); share of area according to environmental report	3.00E+4		
production	wafer area produced			dm2	1.00E+6				2.00E+6	3.89E+6	2.19E+7
lifetime				a	25			Estimation for rapidly changing production facilities, shorter than standard assumption in ecoinvent			

6.8 Meta information of wafers

Tab. 6.7 shows the EcoSpold meta information of different wafers investigated in this chapter.

Tab. 6.7 EcoSpold meta information of different wafers

ReferenceFunction	Name	single-Si wafer, photovoltaics, at plant	single-Si wafer, electronics, at plant	multi-Si wafer, at plant	multi-Si wafer, ribbon, at plant	wafer factory
Geography	Location	RER	RER	RER	RER	DE
ReferenceFuncti	InfrastructureProcess	0	0	0	0	1
ReferenceFuncti	Unit	m2	m2	m2	m2	unit
	IncludedProcesses	Sawing and cleaning of wafers. The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific	Sawing and cleaning of wafers. The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific	Sawing and cleaning of wafers. The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific	Sawing and cleaning of wafers. The process data include electricity use, water and working material consumption (e.g. stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific	Materials and land use for a new production plant.
	LocalName	Wafer, single-Si, Photovoltaik, ab Werk	Wafer, single-Si, Elektronik, ab Werk	Wafer, multi-Si, ab Werk	Wafer, multi-Si, Ribbon, ab Werk	Waferfabrik
	Synonyms	monocrystalline//single crystalline//silicon	monocrystalline//single crystalline//silicon	polycrystalline//multi-crystalline//silicon	polycrystalline//multi-crystalline//silicon	
	GeneralComment	The reference flow for the life cycle inventory is 1 square metre of wafer surface. The sc-Silicon columns are sawn into square wafers with a size 156x156 mm2 (0.0243 m2) and a thickness of 270 um. The weight is 629 g/m2.	The reference flow for the life cycle inventory is 1 square metre of wafer surface. The sc-Silicon columns are sawn into square wafers with a size 156x156 mm2 (0.0243 m2) and a thickness of 270 um. The weight is 629 g/m2.	The reference flow for the life cycle inventory is 1 square metre of wafer surface. The mc-Silicon columns are sawn into square wafers with a size 156x156 mm2 (0.0243 m2) and a thickness 240 um. The weight is 559 g/m2.	The reference flow for the life cycle inventory is 1 square metre of wafer surface. The ribbon silicon wafers have a wafer thickness of 200-300 um. The wafer area is 120-156 cm2, thickness 250 um. The weight is 583 g/m^2	Plants of Wacker, DE in Wasserburg and Freiberg. Capacity of 1 million wafers per year. Life time assumed to be 25 years.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components	production of components	production of components
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	1992	1992	1992	2005	2000
	EndDate	2006	2006	2006	2006	2005
	OtherPeriodText	Collection of data in 2005. Use of data from an environmental report for a production plant (ca. 3 million wafers per year) and some data from older publications.	Collection of data in 2005. Use of data from an environmental report for a production plant (ca. 3 million wafers per year) and some data from older publications.	Collection of data in 2005. Use of data from an environmental report for a production plant (ca. 3 million wafers per year) and some data from older publications.	Use of data from an environmental report for a production plant (ca. 3 million wafers per year) and some data from older publications.	Date of publication.
Geography	Text	Europe, Western + North America	Europe, Western + North America	Europe, Western + North America	Europe, Western + North America	Two plants in DE and literature data.
Technology	Text	Use of multi wire saws.	Use of multi wire saws.	Use of multi wire saws.	Average from 3 specific processes of which one in pilot phase.	Wafer manufacturing plant for electronic and photovoltaics industry.
Representativen	Percent	20	20	20	20	20
	ProductionVolume	7.5E5 m2 in 2005	3.6E4 m2 in 2005	2.6E6 m2 in 2005	Not known.	1 million wafers per year in the factories. 25 years life time.
	SamplingProcedure	Data collection by factory representatives. Environmental report and LCA studies.	Data collection by factory representatives. Environmental report and LCA studies.	Data collection by factory representatives. Environmental report and LCA studies.	Data collection by factory representatives. Environmental report and LCA studies.	Environmental report
	Extrapolations	Rough assumption for electricity use.	own estimation with data for PV wafer	Rough assumption for electricity use.	none	DE data used for Europe.

7 Silicon solar cell production

7.1 Introduction

A solar cell is a kind of semiconductor device that takes advantage of the photovoltaic effect, in which electricity is produced when the semiconductor's pn junction is irradiated (Fig. 7.1). When light strikes a solar cell, part of it is reflected, part of it is absorbed, and part of it passes through the cell. The absorbed light excites the bound electrons into a higher energy state, making them free electrons. These free electrons move about in all directions within the crystal, leaving holes where the electrons used to be, and the holes also shift around the crystal. The electrons (-) collect in the n-layer, the holes (+) in the p-layer. When the outside circuit is closed, electricity flows.[19]

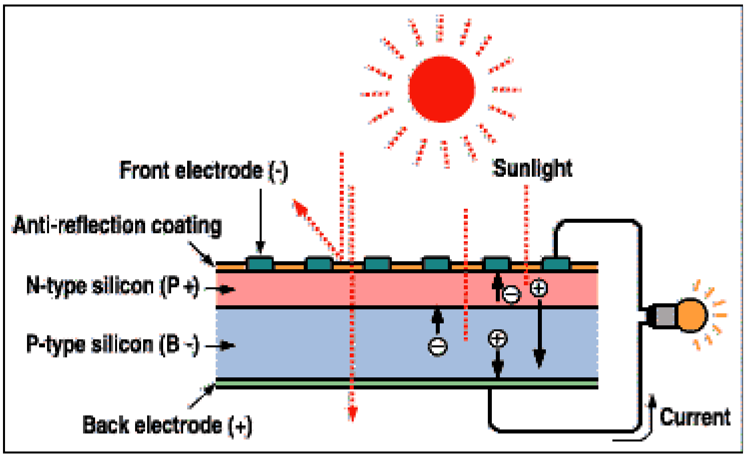


Fig. 7.1 Silicon-solar cell (www.nasolar.com/info.html)

Solar cells are produced in different countries. The following Fig. 7.2 shows the most important producers of solar cells (IEA-PVPS 2006).

[19] www.nasolar.com/info.html

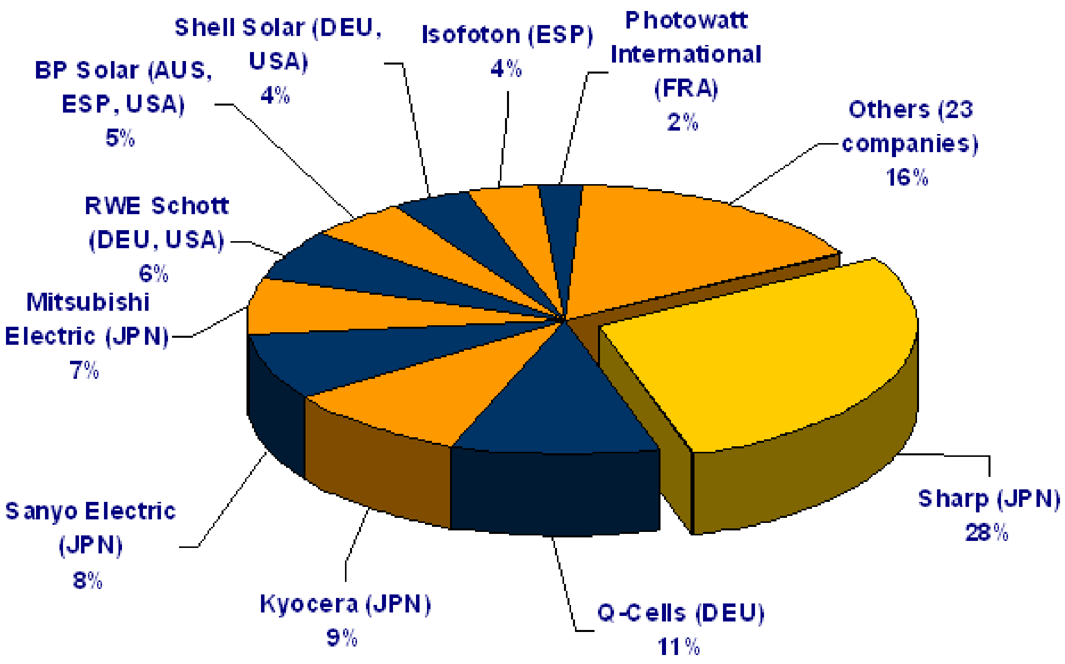


Fig. 7.2 Share of PV cell production in the reporting countries by company in 2005 (%) (IEA-PVPS 2006)

Tab. 7.1 shows the top 12 worldwide manufacturers of PV cells in 2005. The annual survey made by the American review, PV News, reports that 1,727 MWp of photovoltaic cells were produced in 2005, i.e. 44.5% growth with respect to 2004 (1,195 MWp produced). The 2005 ranking of the main industrial producers of photovoltaic cells is representative of the principal cell production zones in the world (Japan, Europe, USA and China).

Tab. 7.1 Top 12 Worldwide manufacturers of PV cells (in MWP)

Companies	2004	2005	Growth in %	Market share 2005
Sharp	324	428	32.1%	24.8%
Q-Cells	75	160	113.3%	9.3%
Kyocera	105	142	35.2%	8.2%
Sanyo	65	125	92.3%	7.2%
Mitsubishi	75	100	33.3%	5.8%
Schott Solar	63	95	50.8%	5.5%
BP Solar	85	90	5.9%	5.2%
Suntech	28	80	185.7%	4.6%
Motech	35	60	71.4%	3.5%
Shell Solar	72	59	-18.1%	3.4%
Isofotón	53	53	0.0%	3.1%
Deutsche Cell	28	38	35.7%	2.2%
Other comppanies	187	297	58.8%	17.2%
Total	**1195**	**1727**	**44.5%**	**100.0%**

Source: PV News, March 2006 shown on www.epia.org and www.energies-renouvelables.org

The life cycle inventory data for this process are mainly based on a recent publication with average data for 5 companies (de Wild-Scholten & Alsema 2007). All these companies produced solar cells by means of the screen printing technology, which is also the most widely used technology in the solar cell industry. Production of buried contact sc-Si cells (as done by BP Solar) has not been considered because no adequate data on this were available.

Further literature has been used to assess missing data (Cherubini 2001; Hagedorn & Hellriegel 1992; Nijs et al. 1997). The differences in the production process for sc-Si, mc-Si and ribbon-Si cells are quite small. The unit process raw data are assumed to be the same for all three types of cells.

7.2 Crystalline cells

7.2.1 Process

The following description shows the main process stages:

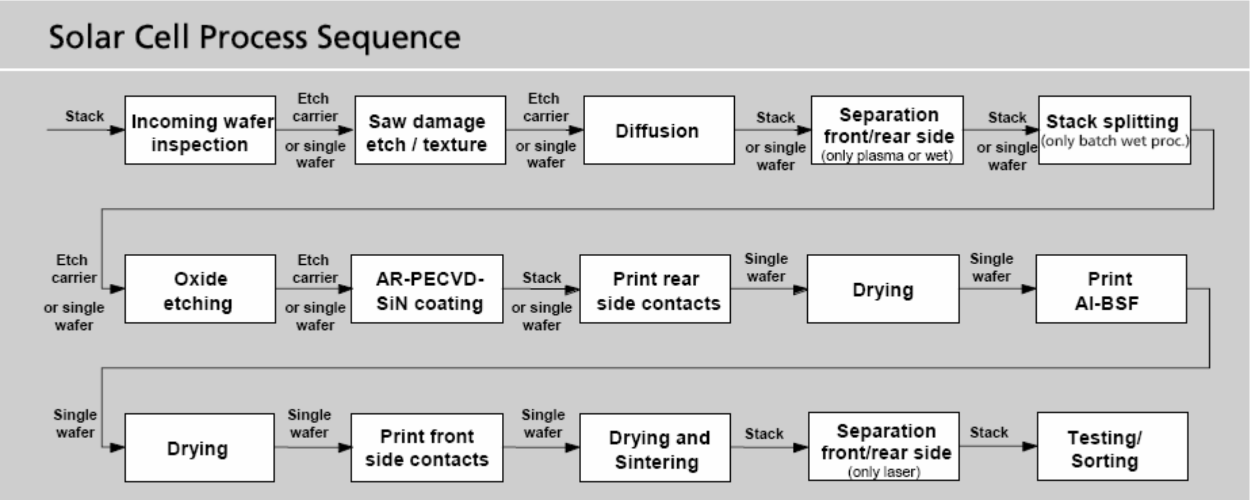
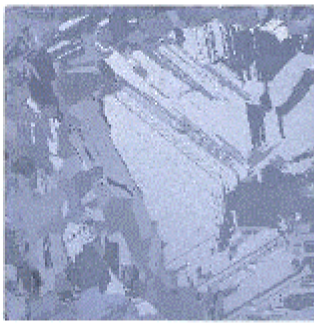


Fig. 7.3 Solar cell production process (Information provided by Centrotherm)

1. The basic input for the process are silicon wafers. Different sizes and thickness are on the market.

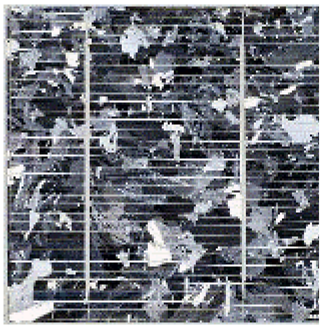


2. Etching: The wafers are first subjected to several chemical baths to remove microscopic damage to their surface. The wafers are etched with alkali in order to remove sawing parts.

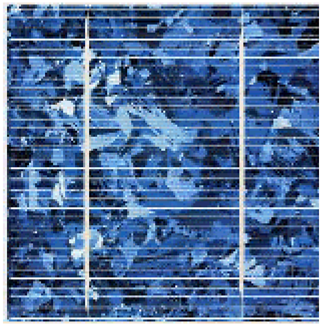
3. The single side polished or mirror-etched wafers that are used for photovoltaic application have to undergo a doping process first in order to create the photo-active p/n junction. This is in most cases a n+ doping with phosphorous. The doping is either done by the deposition of a doping glass and following diffusion in a conveyor furnace or in a tube furnace, using phosporousoxychloride (POCl3). The doping method, using doping glass is simple and can be done in a continuous process in a conveyor furnace. However this method requires two process steps more compared to the POCl3-doping process, because the doping glass has to be deposited and removed. In case that the POCl3-doping is used, in the past horizontal furnaces have been selected in most cases for cost reasons and because of the low demands to this process. The following reaction takes place:

$$2\ PH_3 + 4\ O_2 \rightarrow P_2O_5 + 3\ H_2O^-$$

Then the wafers are coated in order to obtain a negative-conducting film on the surface.



4. A print metallization on the front and backside is made in order to allow the electricity connection. Finally, the printed-on contact material is burnt into the wafer in the furnace.



5. Coating: Anti-reflection coating on the front size in order to improve the efficiency. The finished cell is checked for its efficiency and other electrical as well as visual characteristics and are classified accordingly.

7.2.2 Material inputs

All data for material inputs in Tab. 7.4 are based on a recent survey for 5 companies in the year 2004 (de Wild-Scholten & Alsema 2007). Some inputs and emissions have been aggregated in order to protect sensitive data.

7.2.3 Energy use

Data for the electricity use have been derived from literature (de Wild-Scholten & Alsema 2007). Older data show a large variation for the energy use, but partly they might include also additional process stages (Phylipsen & Alsema 1995). Tab. 7.2 shows an overview for available literature data. Some companies use own photovoltaic plants in order to provide the electricity for the production process (Shell Solar 2000). This has not been taken into account for this study.

Tab. 7.2 Process electricity for solar cells

sc-Si cell	mc-Si cell	Remark
kWh/ dm^2	kWh/ dm^2	
1.3	1.5	(Hagedorn & Hellriegel 1992:116) incl. auxiliary energy
	0.24-3.44	Range for mc-Si in literature (Phylipsen & Alsema 1995)
0.27		(Kato et al. 1997a)
	0.15	(Nijs et al. 1997)
0.6		(Frankl & Gamberale 1998)
0.6	0.6	(Alsema et al. 1998)
1.46		sc-Si (Knapp & Jester 2000b) [1])
	0.11	mc-Si (Cherubini 2001) for Eurosolare, IT
0.2	0.2	(Jungbluth 2003) for a 100 dm2 cell.
	0.13 – 0.4	Calculation based on equipment data[20]
0.302	0.302	(de Wild-Scholten & Alsema 2007)
0.302	**0.302**	**This study**

[1]) The description is quite short. The figure might include also silicon purification (Personal communication Dirk Gürzenich, 12.2002.

7.2.4 Output and emissions

All data for emissions are based on recent literature data (de Wild-Scholten & Alsema 2007). In cell production nitric acid is used for texturing multi-crystalline silicon wafers (alkaline etching for single-crystalline silicon). Specific emission data from a multi-Si cell line were not available; however other authors believe that the NOx emissions –if any– will be low because abatement is easy.[21] They have been estimated here with 50 mg/m^2 (Hagedorn & Hellriegel 1992:92).

In general effluents to water will be quite small. The used acids are neutralized, no heavy metals are expected in the water effluent. In comparison with micro-electronics industry, cell processing is much less material requirement intensive and only small amounts of organic solvents are used.

The concentration of pollutants in the effluents has been calculated with the amount of chemicals used in the process (see Tab. 7.4) and the amount of waste water discharged (217 litre per m^2, de Wild-Scholten & Alsema 2007). The calculated data for the concentration of different substances in the effluents in Tab. 7.3 have than been used to estimate the unit process raw data for the treatment of PV cell production effluents with the model used in ecoinvent (Doka 2003). This dataset is named “treatment, PV cell production effluent, to wastewater treatment, class 3”.

[20] Personal communication with Mariska J. de Wild-Scholten, 12.4.2007

[21] Personal communication with Erik Alsema and Mariska J. de Wild-Scholten, 24.11.2006.

Tab. 7.3 Calculated concentration of water pollutants in effluents from PV cell production used for the modelling of the unit process raw data for "treatment, PV cell production effluent, to wastewater treatment, class 3"

	Name for wastewater:	PV cell production effluent
		mean amount
Total organic carbon **TOC** as C	[kg/m3]	2.70E-01
Ammonia **NH4** as N	[kg/m3]	3.10E-02
Nitrate **NO3** as N	[kg/m3]	1.23E-01
Phosphate **PO4** as P	[kg/m3]	3.53E-02
Chlorine Cl	[kg/m3]	2.73E-01
Fluorine F	[kg/m3]	1.74E-01
Titanium Ti	[kg/m3]	3.91E-06
Silicon Si	[kg/m3]	3.50E-01
Calcium Ca	[kg/m3]	3.61E-02
Potassium K	[kg/m3]	7.34E-03
Sodium Na	[kg/m3]	4.15E-01
Capacity class of WWTP	–	3

7.3 Ribbon silicon solar cells

Ribbon Si cells are produced in a similar way as the other Si-cells. There are small differences, but quantitative data specific for ribbon cells were not available. The main differences are as follows:[22]

- Because the surface of the produced ribbons has no roughness, they are very difficult to texture and different (highly confidential) mixtures are used compared to multi- and singlecrystalline silicon.
- Because the surface of the ribbons is not flat and because the crystal quality is less, they break more easily. The yield data have not been corrected accordingly in the ribbon wafer record. Thus, the higher loss is not taken into account in the stage cell processing, but in the stage wafer production (Tab. 6.5).

7.4 Life cycle inventory of solar cells

The unit process raw data in Tab. 7.4 are investigated per m^2. The production of solar cells with a size of 156x156 mm^2 includes cleaning and etching of the wafers. Afterwards wafers are doped with phosphorus and after further etching processes to remove the phosphorus silicate glass, SiN (or TiO2) deposition, front and rear contacts are printed and fired. Process data include working material consumption (acids, oxygen, nitrogen and highly purified water), electricity consumption and production wastes.

Furthermore process-specific air- and waterborne pollutants are considered, mainly hydrocarbons and acids. A part of the solar cells used in Europe is imported from overseas. Thus, additional transport by ship for 2000 km is assumed. This equals a share of 20% for imports with a total distance of 10'000 km. Other possible differences for the production in Europe and Overseas have not been considered.

Cell efficiencies are estimated with data provided by several different producers for their actual products. The information can be found in Tab. 14.3. They are used in the inventory for the electricity production.

[22] Personal communication with Erik Alsema and Mariska J. de Wild-Scholten, 24.11.2006.

Tab. 7.4 Unit process raw data of solar cells in this study

	Name	Location	InfrastructureProcess	Unit	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	photovoltaic cell, ribbon-Si, at plant	StandardDeviation	GeneralComment
	Location				RER	RER	RER		
	InfrastructureProcess				0	0	0		
	Unit				m2	m2	m2		
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	9.99E-1	9.99E-1	9.99E-1	1.07	(1,2,1,1,1,3); de Wild 2007, company data
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	3.02E+1	3.02E+1	3.02E+1	1.07	(1,2,1,1,1,3); de Wild 2007, company data
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	4.77E+0	4.77E+0	4.77E+0	1.07	(1,2,1,1,1,3); de Wild 2007, company data
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	1.16E+0	1.16E+0	1.16E+0	1.07	(1,2,1,1,1,3); de Wild 2007, company data
infrastructure	photovoltaic cell factory	DE	1	unit	4.00E-7	4.00E-7	4.00E-7	3.00	(1,2,1,1,1,3); estimation with company data
wafers	single-Si wafer, photovoltaics, at plant	RER	0	m2	1.06E+0	-	-	1.07	(1,2,1,1,1,3); de Wild 2007, 6% losses
	multi-Si wafer, at plant	RER	0	m2	-	1.06E+0	-	1.07	(1,2,1,1,1,3); de Wild 2007, 6% losses
	multi-Si wafer, ribbon, at plant	RER	0	m2	-	-	1.08E+0	1.07	(1,2,1,1,1,3); de Wild 2007, 7% losses
materials	metallization paste, front side, at plant	RER	0	kg	7.40E-3	7.40E-3	7.40E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for electric contacts
	metallization paste, back side, at plant	RER	0	kg	4.93E-3	4.93E-3	4.93E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for electric contacts
	metallization paste, back side, aluminium, at plant	RER	0	kg	7.19E-2	7.19E-2	7.19E-2	1.07	(1,2,1,1,1,3); de Wild 2007, for electric contacts
chemicals	ammonia, liquid, at regional storehouse	RER	0	kg	6.74E-3	6.74E-3	6.74E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for de-oxidation
	phosphoric acid, fertiliser grade, 70% in H2O, at plant	GLO	0	kg	7.67E-3	7.67E-3	7.67E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for emitter formation. I.e. Ferro FX99-014: hazardous components 1-5% P2O5, 40-90% organic chemicals.
	phosphoryl chloride, at plant	RER	0	kg	1.59E-3	1.59E-3	1.59E-3	1.07	(1,2,1,1,1,3); de Wild 2007, POCl3 for emitter formation
	titanium dioxide, production mix, at plant	RER	0	kg	1.42E-6	1.42E-6	1.42E-6	1.07	(1,2,1,1,1,3); de Wild 2007, tetraisopropyltitanate (TPT, a titanium precursor) for titanium dioxide antireflection coating deposition
	ethanol from ethylene, at plant	RER	0	kg	6.41E-4	6.41E-4	6.41E-4	1.07	(1,2,1,1,1,3); de Wild 2007, for cleaning
	isopropanol, at plant	RER	0	kg	7.89E-2	7.89E-2	7.89E-2	1.07	(1,2,1,1,1,3); de Wild 2007, for cleaning
	solvents, organic, unspecified, at plant	GLO	0	kg	1.43E-3	1.43E-3	1.43E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for cleaning
	silicone product, at plant	RER	0	kg	1.21E-3	1.21E-3	1.21E-3	1.07	(1,2,1,1,1,3); de Wild 2007, silane (SiH4) for silicon nitride deposition
	sodium silicate, spray powder 80%, at plant	RER	0	kg	7.48E-2	7.48E-2	7.48E-2	1.07	(1,2,1,1,1,3); de Wild 2007
	calcium chloride, CaCl2, at regional storage	CH	0	kg	2.16E-2	2.16E-2	2.16E-2	1.07	(1,2,1,1,1,3); de Wild 2007
	acetic acid, 98% in H2O, at plant	RER	0	kg	2.83E-3	2.83E-3	2.83E-3	1.07	(1,2,1,1,1,3); de Wild 2007, for cleaning
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	4.56E-2	4.56E-2	4.56E-2	1.07	(1,2,1,1,1,3); de Wild 2007, for surface etching
	hydrogen fluoride, at plant	GLO	0	kg	3.77E-2	3.77E-2	3.77E-2	1.07	(1,2,1,1,1,3); de Wild 2007, for etching phosphor glass
	nitric acid, 50% in H2O, at plant	RER	0	kg	2.67E-2	2.67E-2	2.67E-2	1.07	(1,2,1,1,1,3); de Wild 2007, for etching phosphor glass
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.57E-1	1.57E-1	1.57E-1	1.07	(1,2,1,1,1,3); de Wild 2007, for etching and cleaning
gases	argon, liquid, at plant	RER	0	kg	2.57E-2	2.57E-2	2.57E-2	1.07	(1,2,1,1,1,3); de Wild 2007, company data
	oxygen, liquid, at plant	RER	0	kg	1.02E-1	1.02E-1	1.02E-1	1.07	(1,2,1,1,1,3); de Wild 2007, diffusion
	nitrogen, liquid, at plant	RER	0	kg	1.85E+0	1.85E+0	1.85E+0	1.07	(1,2,1,1,1,3); de Wild 2007, diffusion and damage etching
	tetrafluoroethylene, at plant	RER	0	kg	3.16E-3	3.16E-3	3.16E-3	1.07	(1,2,1,1,1,3); de Wild 2007, aggregate value for different fluorinated source gases
packaging	polystyrene, expandable, at plant	RER	0	kg	4.07E-4	4.07E-4	4.07E-4	1.07	(1,2,1,1,1,3); de Wild 2007, packaging
transport	transport, transoceanic freight ship	OCE	0	tkm	3.06E-2	3.06E-2	3.06E-2	2.09	(4,5,na,na,na,na); 20% of wafer production from overseas, 10000km
	transport, lorry >16t, fleet average	RER	0	tkm	2.75E-1	2.74E-1	2.74E-1	2.09	(4,5,na,na,na,na); Standard distance 100km, 500km for wafers
	transport, freight, rail	RER	0	tkm	1.52E+0	1.52E+0	1.52E+0	2.09	(4,5,na,na,na,na); Standard distance 600km
	water, completely softened, at plant	RER	0	kg	1.37E+2	1.37E+2	1.37E+2	1.07	(1,2,1,1,1,3); de Wild 2007, company data
	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	2.17E-1	2.17E-1	2.17E-1	1.07	(1,2,1,1,1,3); de Wild 2007, company data, mix of neutral, alkaline and acid solution and organic waste
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	2.76E-1	2.76E-1	2.76E-1	1.07	(1,2,1,1,1,3); de Wild 2007, company data
emission air, high population density	Heat, waste	-	-	MJ	1.09E+2	1.09E+2	1.09E+2	1.07	(1,2,1,1,1,3); Calculation
	Aluminum	-	-	kg	7.73E-4	7.73E-4	7.73E-4	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	Ethane, hexafluoro-, HFC-116	-	-	kg	1.19E-4	1.19E-4	1.19E-4	1.51	(1,2,1,1,1,3); de Wild 2007, calculated as 50% of CO2-eq for FC-gases
	Hydrogen chloride	-	-	kg	2.66E-4	2.66E-4	2.66E-4	1.51	(1,2,1,1,1,3); de Wild 2007, company data
	Hydrogen fluoride	-	-	kg	4.85E-6	4.85E-6	4.85E-6	1.51	(1,2,1,1,1,3); de Wild 2007, company data
	Lead	-	-	kg	7.73E-4	7.73E-4	7.73E-4	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.94E-1	1.94E-1	1.94E-1	1.51	(1,2,1,1,1,3); de Wild 2007, company data
	Nitrogen oxides	-	-	kg	5.00E-5	5.00E-5	5.00E-5	1.61	(3,4,3,3,1,5); Hagedorn 1992, due to nitric acid use
	Methane, tetrafluoro-, R-14	-	-	kg	2.48E-4	2.48E-4	2.48E-4	1.51	(1,2,1,1,1,3); de Wild 2007, calculated as 50% of CO2-eq for FC-gases
	Particulates, < 2.5 um	-	-	kg	2.66E-3	2.66E-3	2.66E-3	3.00	(1,2,1,1,1,3); de Wild 2007, company data
	Silicon	-	-	kg	7.27E-5	7.27E-5	7.27E-5	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	Silver	-	-	kg	7.73E-4	7.73E-4	7.73E-4	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	Sodium	-	-	kg	4.85E-5	4.85E-5	4.85E-5	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	Tin	-	-	kg	7.73E-4	7.73E-4	7.73E-4	5.00	(1,2,1,1,1,3); de Wild 2007, company data
	weight, cell			kg	0.015	0.014	0.014		
	weight, materials			kg	2.53	2.53	2.53		

In Tab. 7.5 the actual used and older literature data are shown for the production of solar cells. Older figures for materials and inputs, which are not used anymore, are not considered for the unit process data shown in Tab. 7.4. Parts of these inputs are included in newly investigated materials like the metallization paste.

Tab. 7.5 Older literature data of solar cell production (Cherubini 2001; Jungbluth 2003; Nijs et al. 1997 and data used in this study (de Wild-Scholten & Alsema 2007)

	3702	3703	###	3706	3707	*de Wild 2007*	*ecoinvent v1.3*	*ecoinvent v1.3*	*Cherubini 2001*	*Nijs 1997*
	Name	Location	InfrastructureProcess	Unit	photovoltaic cell, single-Si, at plant	*mc- or pc-Si cell*	*cell, sc-Si*	*cell, pc-Si*	*pc-Si cell*	*pc-Si cell*
	Location				RER	*RER*	*RER*	*RER*	*IT*	*GLO*
	InfrastructureProcess				0	*0*	*0*	*0*	*0*	*0*
	Unit				m2	*m2*	*m2*	*m2*	*m2*	*m2*
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	3.02E+1	3.02E+1	2.00E+1	2.00E+1	1.07E+1	-
infrastructure	photovoltaic cell factory	DE	1	unit	4.00E-7	-	4.00E-7	4.00E-7	-	-
wafers	single-Si wafer, photovoltaics, at plant	RER	0	m2	1.06E+0	1.06E+0	1.05E+2	-	-	-
	multi-Si wafer, ribbon, at plant	RER	0	m2	-	1.06E+0	-	1.09E+2	-	-
chemicals	ammonia, liquid, at regional storehouse	RER	0	kg	6.74E-3	6.74E-3	1.30E-2	2.40E-2	2.36E-2	-
	phosphoryl chloride, at plant	RER	0	kg	1.59E-3	1.59E-3	5.00E-2	1.30E-2	1.56E-1	-
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	4.56E-2	4.56E-2	-	1.50E-1	1.48E-1	6.00E-1
	hydrogen fluoride, at plant	GLO	0	kg	3.77E-2	3.77E-2	1.80E-1	1.80E-1	1.83E-1	3.00E-1
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.57E-1	1.57E-1	2.90E-1	2.90E-1	2.88E-1	3.40E-1
	oxygen, liquid, at plant	RER	0	kg	1.02E-1	1.02E-1	4.00E-3	4.60E+0	-	-
	nitrogen, liquid, at plant	RER	0	kg	1.85E+0	1.85E+0	1.55E-1	1.55E-1	-	4.25E+0
transport	transport, transoceanic freight ship	OCE	0	tkm	3.06E-2		1.40E+0	1.40E+0	-	-
	transport, lorry >16t, fleet average	RER	0	tkm	2.75E-1		8.87E-2	5.65E-1	-	-
	transport, freight, rail	RER	0	tkm	1.52E+0		4.15E-1	3.25E+0	-	-
	water, completely softened, at plant	RER	0	kg	1.37E+2	1.37E+2	3.20E+2	3.20E+2	-	3.20E+2
	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	2.76E-1	2.76E-1	3.90E-1	4.76E-1	-	-
emission air, high population density	Heat, waste	-	-	MJ	1.09E+2	-	7.20E+1	7.20E+1	-	-
	Hydrogen fluoride	-	-	kg	4.85E-6	4.85E-6	9.00E-3	-	-	-
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.94E-1	1.94E-1	4.00E-2	3.40E-2	-	-
	Nitrogen oxides	-	-	kg	5.00E-5	2.67E-2	-	5.00E-5	-	-
	weight, materials			kg	2.53	2.53E+0	6.92E-1	5.41E+0	7.99E-1	5.49E+0
resource, in ground	Silver, 0.01% in crude ore, in ground	-	-	kg	-	-	3.80E-2	4.50E-2	9.86E-3	1.50E-2
technosphere	ethylene glycol, at plant	RER	0	kg	-	-	5.60E-1	-	-	-
	lime, hydrated, packed, at plant	CH	0	kg	-	-	3.40E-1	4.20E-1	-	-
	lubricating oil, at plant	RER	0	kg	-	-	-	1.00E-4	-	-
	hydrogen, liquid, at plant	RER	0	kg	-	-	-	3.00E-4	-	-
	chemicals organic, at plant	GLO	0	kg	-	-	1.00E-1	7.00E-2	7.55E-2	-
emission	Carbon dioxide, fossil	-	-	kg	-	-	-	3.00E-3	-	-

7.5 Infrastructure of solar cell manufacturing

The life cycle inventory for the solar cell manufacturing plant includes the land use and buildings. The data are based on information in literature (de Wild-Scholten & Alsema 2007; Shell Solar 2000). Tab. 7.6 shows the unit process raw data of a solar cell factory.

Tab. 7.6 Unit process raw data of the infrastructure for solar cell production, lifetime 25 years, annual production 10 Million solar cells of 10 dm2

	Name	Location	Infrastruc	Unit	photovoltaic cell factory	Uncertai	Standard Deviation	GeneralComment	*Production plant Gelsenkirchen*	*Crystal Clear*
	Location				DE				*DE*	*RER*
	InfrastructureProcess				1				*1*	*1*
	Unit				unit				*unit*	*unit*
product	photovoltaic cell factory	DE	1	unit	1.00E+0				*Total*	
technosphere	reinforcing steel, at plant	RER	0	kg	1.90E+5	1	1.51	(1,2,1,1,1,3); Company information	1.90E+5	
	steel, low-alloyed, at plant	RER	0	kg	1.10E+5	1	1.51	(1,2,1,1,1,3); Company information	1.10E+5	
	brick, at plant	RER	0	kg	5.06E+2	1	1.51	(1,2,1,1,1,3); Company information	5.06E+2	
	concrete, normal, at plant	CH	0	m3	1.80E+3	1	1.51	(1,2,1,1,1,3); Company information	1.80E+3	
	metal working machine, unspecified, at plant	RER	1	kg	1.00E+4	1	1.78	(5,3,1,1,1,3); Rough estimation equipment		
	transport, lorry >16t, fleet average	RER	0	tkm	4.27E+5	1	1.51	(1,2,1,1,1,3); Standard distances		
	transport, freight, rail	RER	0	tkm	4.58E+5	1	1.51	(1,2,1,1,1,3); Standard distances		
	disposal, building, brick, to sorting plant	CH	0	kg	5.06E+2	1	1.51	(1,2,1,1,1,3); Estimation		
	disposal, building, reinforced concrete, to sorting plant	CH	0	kg	3.96E+6	1	1.51	(1,2,1,1,1,3); Estimation		
	disposal, building, reinforcement steel, to sorting plant	CH	0	kg	3.00E+5	1	1.51	(1,2,1,1,1,3); Estimation		
resource, land	Occupation, industrial area, built up	-	-	m2a	4.31E+4	1	1.51	(1,2,1,1,1,3); 25a occupation, estimation for rapid changing technology		
	Occupation, industrial area, vegetation	-	-	m2a	2.50E+4	1	2.00	(1,2,1,1,1,3); 25a occupation, estimation for rapid changing technology		
	Transformation, from unknown	-	-	m2	2.73E+3	1	2.00	(1,2,1,1,1,3); Company information		
	Transformation, to industrial area, built up	-	-	m2	1.73E+3	1	2.00	(1,2,1,1,1,3); averaged company information	3.90E+3	1.60E+3
	Transformation, to industrial area, vegetation	-	-	m2	1.00E+3	1	2.00	(1,2,1,1,1,3); Company information	1.00E+3	
	annual production, cell area			dm2	1.00E+7				1.00E+7	2.19E+7

7.6 Life cycle inventory of metallization paste

The unit process raw data for the production of metallization pastes are shown in Tab. 7.7. The main data for the amount of used materials are provided by the CrystalClear project (de Wild-Scholten & Alsema 2007). The silver content of pastes is very confidential information, because the silver is a main cost component of the paste. The estimates are based on material safety data sheet (MSDS) info, but these give fairly wide ranges. So there is some uncertainty about this, but actually the total weight of the materials used is fixed to about one kilogram. The uncertainty of shares cannot be shown in ecoinvent data. Data for the energy use and infrastructure have been estimated with data for the production of solders (Classen et al. 2007).

Tab. 7.7 Unit process raw data of metallization pastes

	Name	Location	InfrastructureProcess	Unit	metallization paste, front side, at plant	metallization paste, back side, at plant	metallization paste, back side, aluminium, at plant	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER		
	InfrastructureProcess				0	0	0		
	Unit				kg	kg	kg		
product	metallization paste, front side, at plant	RER	0	kg	1.00E+0	0	0		
	metallization paste, back side, at plant	RER	0	kg	0	1.00E+0	0		
	metallization paste, back side, aluminium, at plant	RER	0	kg	0	0	1.00E+0		
technosphere	silver, at regional storage	RER	0	kg	8.38E-1	6.77E-1	-	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	lead, at regional storage	RER	0	kg	5.05E-2	8.08E-2	-	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss, bismuth inventoried as lead.
	aluminium, primary, at plant	RER	0	kg	-	-	8.08E-1	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	silica sand, at plant	DE	0	kg	-	-	3.03E-2	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
	chemicals organic, at plant	GLO	0	kg	1.21E-1	2.53E-1	1.72E-1	1.13	(3,2,1,1,1,3); de Wild 2007, paste composition, 1% loss
energy	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	2.50E-1	2.50E-1	2.50E-1	1.52	(3,na,2,1,4,na); Estimation with data for solder production
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	8.28E-1	8.28E-1	8.28E-1	1.52	(3,na,2,1,4,na); Estimation with data for solder production
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.01E-1	1.01E-1	1.01E-1	2.09	(4,5,na,na,na,na); Standard distance 100km
	transport, freight, rail	RER	0	tkm	6.06E-1	6.06E-1	6.06E-1	2.09	(4,5,na,na,na,na); Standard distance 600km
	solder production plant	RER	1	unit	2.00E-10	2.00E-10	2.00E-10	3.09	(4,5,na,na,na,na); Esimation
emission air	Heat, waste	-	-	MJ	9.00E-1	9.00E-1	9.00E-1	1.29	(3,4,3,3,1,5); Calculation
	total material weight			kg	1.01	1.01	1.01		

7.7 Meta information of silicon cells

Tab. 7.8 show the EcoSpold meta information of silicon cells investigated in this chapter.

Tab. 7.8 EcoSpold meta information of silicon cell production

ReferenceFunction	Name	photovoltaic cell, single-Si, at plant	photovoltaic cell, multi-Si, at plant	photovoltaic cell, ribbon-Si, at plant	metallization paste, front side, at plant	metallization paste, back side, at plant	metallization paste, back side, aluminium, at plant	photovoltaic cell factory
Geography	Location	RER	RER	RER	RER	RER	RER	DE
ReferenceFuncti	InfrastructureProcess	0	0	0	0	0	0	1
ReferenceFuncti	Unit	m2	m2	m2	kg	kg	kg	unit
	IncludedProcesses	Cleaning, damage etching, texture etching, covering of backside, phosphor dotation, phosphor glass etching, printing of contacts, cleaning and quality testing.	Cleaning, damage etching, texture etching, covering of backside, phosphor dotation, phosphor glass etching, printing of contacts, cleaning and quality testing.	Cleaning, damage etching, texture etching, covering of backside, phosphor dotation, phosphor glass etching, printing of contacts, cleaning and quality testing.	Production of paste used in production of photovoltaic cells.	Production of paste used in production of photovoltaic cells.	Production of paste used in production of photovoltaic cells.	Materials and land use for a new production plant.
	LocalName	Solarzelle, single-Si, ab Werk	Solarzelle, multi-Si, ab Werk	Solarzelle, ribbon-Si, ab Werk	Metallisierungspaste, Vorderseite, ab Werk	Metallisierungspaste, Rückseite, ab Werk	Metallisierungspaste, Rückseite, Aluminium, ab Werk	PV-Zellenfabrik
	Synonyms	monocrystalline//single crystalline//silicon	polycrystalline//multi-crystalline//silicon	polycrystalline//multi-crystalline//silicon				
	GeneralComment	Production of photovoltaic cells (156*156 mm2). Some inputs and emissions aggregated to protect sensitive data. Wafer thickness 270-300 um. with an efficiency of 15.4% and 1.5Wp	Production of photovoltaic cells (156*156 mm2). Some inputs and emissions aggregated to protect sensitive data. Wafer thickness 270-300 um. With an efficiency of 13.5% and 1.3Wp.	Production of photovoltaic cells (156*156 mm2). Some inputs and emissions aggregated to protect sensitive data. with an efficiency of 15%. Wafer thickness 270-300 um.	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.	Chemical composition of typical pastes taken from Material Safety Data Sheets. Energy use and infrastructure estimated with data for solder production.	New plant of Shell Solar in Gelsenkirchen. Capacity of 10 million solar cells per year. Life time assumed to be 25 years.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components	production of components	production of components	production of components	production of components
	Formula							
	StatisticalClassification							
	CASNumber							
TimePeriod	StartDate	2004	2004	2004	2006	2006	2006	2000
	EndDate	2005	2005	2005	2006	2006	2006	2005
	OtherPeriodText	Data investigated in 2004 and recalculated for the cell size in 2005.	Data investigated in 2004 and recalculated for the cell size in 2005.	Data investigated in 2004 and recalculated for the cell size in 2005.	Data investigated in 2006.	Data investigated in 2006.	Data investigated in 2006.	Date of publication.
Geography	Text	Data for production in Europe.	Data for production in Europe.	Data for production in Europe.	Data for production in Europe.	Data for production in Europe.	Data for production in Europe.	Gelsenkirchen, DE.
Technology	Text	Average production technology of photovoltaic cells from wafers.	Average production technology of photovoltaic cells from wafers.	Average production technology of photovoltaic cells from wafers.	Assumption that production technology is similar as for solders.	Assumption that production technology is similar as for solders.	Assumption that production technology is similar as for solders.	New plant on old industrial site.
Representativen	Percent	6	6	6				6
	ProductionVolume	Total worldwide production 243MW in 2000. Europe 37MW.	Total worldwide production 243MW in 2000. Europe 37MW.	Total worldwide production 243MW in 2000. Europe 37MW.	not known	not known	not known	10 million cells/a in the factory. Total worldwide production ca 170 million
	SamplingProcedure	Data collected from 5 specific processes and companies (4 multi-Si + 1 single-Si processing company).	Data collected from 5 specific processes and companies (4 multi-Si + 1 single-Si processing company).	Data collected from 5 specific processes and companies (4 multi-Si + 1 single-Si processing company).	Chemical composition of typical pastes taken from Material Safety Data Sheets.	Chemical composition of typical pastes taken from Material Safety Data Sheets.	Chemical composition of typical pastes taken from Material Safety Data Sheets.	Information on webpage.
	Extrapolations	Data 2005 calculated from data 2004 by multiplying amounts of materials by solar cell area factor of 156*156/(125*125) = 1.56; energy scaled linearly with	Data 2005 calculated from data 2004 by multiplying amounts of materials by solar cell area factor of 156*156/(125*125) = 1.56; energy scaled linearly with	Data 2005 calculated from data 2004 by multiplying amounts of materials by solar cell area factor of 156*156/(125*125) = 1.56; energy scaled linearly with	Other data investigated with information from solder production.	Other data investigated with information from solder production.	Other data investigated with information from solder production.	none

8 PV panel and laminate production

8.1 Introduction

Here we investigate the production of solar panels and laminates. Another expression for panels is PV-modules, that is not used here in order to avoid confusion with the meaning of module in the context of LCA.

The trend is to increase the size of panels and modules in order to facilitate the installation. Most of the panels found on the market have 60-72 mc-cells. Here we investigate a panel with 60 cells of 156 by 156 mm^2 because the main literature sources investigated this size. The panel has a width of 98.6 cm and a length of 162 cm (de Wild-Scholten & Alsema 2007). The production of panels and laminates with sc-Si, mc-Si or ribbon-Si cells is quite similar. Thus, all products are investigated with the same data.

Fig. 8.1 shows the share of different PV-module producers for the total worldwide production. The total production in 2005 was 1500 MWp. The production capacity is about 2500 MWp (IEA-PVPS 2006). About 50% of all of the panels used in Switzerland are produced in the country (Jauch & Tscharner 2006). All solar cells used for production in Switzerland are imported to the country. Thus, an average production in Europe is investigated for the life cycle inventory.

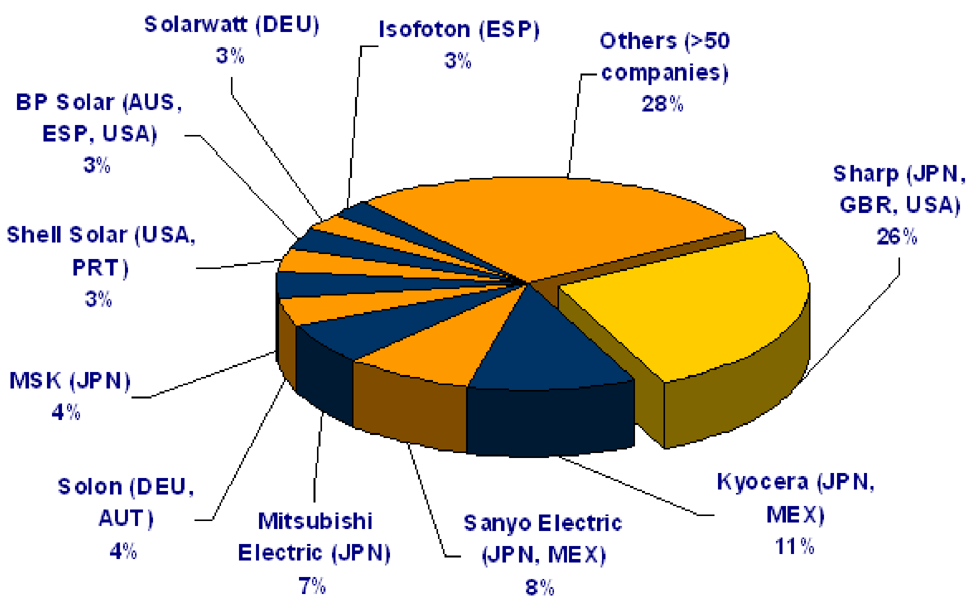


Fig. 8.1 Share of PV module production in the reporting countries by company in 2005 (%) (IEA-PVPS 2006)

8.2 Process for production of PV panels

The process is described according to literature information (Hagedorn 1992; Shell Solar 2000; Solar-Fabrik 2002).

First a cell string is produced connecting the cells with copper connections. The solar cells are embedded in layers of ethyl-vinylacetate (one each on the front and the back). The rear cover consists of a polyester and polyvinylfluoride (Tedlar) film. A 4 mm low-iron glass sheet is used for the front cover. The sandwich is joined under pressure and heat, the edges are purified and the connections are insulated. Small amounts of gases might be emitted to air. Overlaying parts of the foil are cut-off. The panel gets additionally an aluminium frame (AlMg3). A connection box is installed. Silicones might be used for fitting. Laminates are modules without a frame that can directly be integrated into the building. Finally, panels and laminates are tested and packed.

The process data include materials and energy consumption as well as the treatment of production wastes.

8.3 Materials

The use of materials has been investigated in different publications. As a basic assumption we use the data investigated in 2005 for 2 companies and an additional literature research (de Wild-Scholten & Alsema 2007). Some assumptions are based on environmental reports and older literature data (GSS 2001).

Data for GSS (2001) in Germany were available from an environmental report. It is assumed that the total production was about 18'000 panels.

Data are also available for other manufacturers, but they have not been used, because more recent data were available (Hagedorn 1992; Solon AG 2001). Changes show the improvements achieved in the last time.

Tab. 8.2 shows the unit process raw data used for the life cycle inventory and the literature data.

8.4 Energy use

The energy use for the panel manufacturing is not very important in comparison to energy uses in other stages of the total PV production process. The main energy use is heat for the lamination process. Auxiliary energy for light and air-condition or heating might account for about 50% of the total use. Tab. 8.1 shows the energy use investigated in different studies. The available figures are quite different. Reasons might be different necessity for the use of air-conditioning or heating. Some producer use own PV-plants for producing a part of the necessary electricity (Shell Solar 2000; Solar-Fabrik 2002), others (GSS 2001; Solon AG 2001) use only electricity from the grid. One company uses only renewable energy source including photovoltaics and bioenergy (Solar-Fabrik 2002).

Here we use for the heat and electricity use average figures from different environmental reports (de Wild-Scholten & Alsema 2007; GSS 2001; Shell Solar 2000; Solar-Fabrik 2002; 2007; Solon AG 2001). The replacement of standard cure EVA by fast cure EVA may reduce the energy consumption in the future.[23]

Tab. 8.1 Energy consumption for the production of PV panels. Own recalculation per m^2. Cursive figures are assumed to be outdated.

Electricity	Heat	
kWh	MJ	
27	*0*	(Solon AG 2001), many special products, natural gas will be used for heating in future.
4.1	*4.2*	(Solar-Fabrik 2002) heat produced from rapeseed oil, electricity ca. 50% from rapeseed oil, 15% from PV, rest eco-electricity from the grid.
0.77	4.7	Solar-Fabrik 2007)
6.5	11.5	(GSS 2001)
6.8	0	(de Wild-Scholten & Alsema 2007) for one company in Portugal
4.7	**5.4**	**This study (average of 3 most recent figures not cursive)**

[23] Personal communication Mariska de Wild-Scholten, 10.3.2007.

8.5 Emissions

Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the lamination process.

The amount of effluents in Tab. 8.2 has been calculated with the same figure as water use.

For production wastes the amount has been estimated with 1kg/panel based on data provided in an environmental report (GSS 2001). Auxiliary materials from the process are treated in waste incineration.

8.6 Recycling and disposal of PV panels

As the panel is an infrastructure module, the whole disposal after use is also taken into account. At the moment there are different initiatives for establishing a recycling scheme for used PV panels, but so far the amount of disposed panels is quite small (Wambach 2002). Thus real experiences are not available. So far the small amounts of damaged panel are treated e.g. by incineration or in land fills.

It can be expected that glass, aluminium frame and the silicon cells will be recycled in future. Also electronic parts should be treated in existing recycling facilities for electric devices. Different possibilities for recycling are discussed in (Fthenakis 2000; Müller et al. 2004; Wambach 2002; Warmbach et al. 2004).

In this study (Tab. 8.2) we assume a recycling for the glass, metal and silicon materials. According to the ecoinvent guidelines no input or output shows up. Other materials as e.g. the EVA foil are treated by waste incineration.

8.7 Life cycle inventory of PV panels and laminates

Tab. 8.2 shows the unit process raw data of PV panels and laminates with sc-Si cells as an example. Similar data are used for ribbon silicon and mc-Si cells. The variability for the panel size and the amounts of cells per panel between different producers is high. But, possible small differences e.g. due to different amount of cells per m^2 of panel are not taken into account. The reference flow is one panel or laminate with a size of 162×98.6 cm^2. The data are calculated per m^2 of panel area. The panel capacity is considered in the inventory for the electricity production (see Tab. 11.2). For laminates the same flows are recorded except the use of aluminium for the frame.

The data quality in general is quite good because recent data from producers and environmental reports could be used. But, for the energy use quite varying figures have been found, which need further verification in future studies. No data are available for possible process specific NMVOC emissions.

Tab. 8.2 Unit process raw data of solar panels and laminates produced with silicon solar cells and literature data

	Name	Location	InfrastructureProcess	Unit	photovoltaic laminate, single-Si, at plant	photovoltaic panel, single-Si, at plant	Uncertainty	Standard Deviation	GeneralComment	de Wild 2007, 210 Wp	Solar-Fabrik	GSS Ostthüringen, 160 Wp	Solon AG	Solar-Fabrik
	Location				RER	RER				RER	DE	DE	DE	DE
	InfrastructureProcess				1	1				2005	2006	2001	2000	2001
	Unit				m2	m2				m2	m2	m2	m2	m2
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	4.71E+0	4.71E+0	1	1.14	(3,3,1,1,1,3); calculated mean figure of 3 companies	6.83E+0	7.66E-1	6.54E+0	2.73E+1	4.09E+0
	natural gas, burned in industrial furnace low-NOx >100kW	RER	0	MJ	5.41E+0	5.41E+0	1	1.14	(3,3,1,1,1,3); calculated mean figure of 3 companies	-	4.72E+0	1.15E+1		4.25E+0
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	4.00E-6	1	3.02	(1,4,1,3,1,3); Literature			-		
	tap water, at user	RER	0	kg	2.13E+1	2.13E+1	1	1.13	(1,4,1,3,1,3); de Wild 2007, glass rinsing and general use	2.13E+1		2.19E+1		
	tempering, flat glass	RER	0	kg	1.01E+1	1.01E+1	1	1.13	(1,4,1,3,1,3); de Wild 2007					
	wire drawing, copper	RER	0	kg	1.13E-1	1.13E-1	1	1.13	(1,4,1,3,1,3); estimation for use of copper wires					
cells	photovoltaic cell, single-Si, at plant	RER	0	m2	9.32E-1	9.32E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, Estimation 60 cells a 1.56dm2 +2% cell loss	9.32E-1		6.85E+1		
	photovoltaic cell, multi-Si, at plant	RER	0	m2	-	-	1	1.13	(1,4,1,3,1,3); de Wild 2007, Estimation 60 cells a 1.56dm2 +2% cell loss	9.32E-1		-		
	photovoltaic cell, ribbon-Si, at plant	RER	0	m2	-	-	1	1.13	(1,4,1,3,1,3); de Wild 2007, Estimation 60 cells a 1.56dm2 +2% cell loss	9.32E-1				
materials	aluminium alloy, AlMg3, at plant	RER	0	kg	-	2.63E+0	1	1.13	(1,4,1,3,1,3); de Wild 2007, profile for frame	2.63E+0		2.40E+0		
	nickel, 99.5%, at plant	GLO	0	kg	1.63E-4	1.63E-4	1	1.13	(1,4,1,3,1,3); de Wild 2007, plating on interconnect ribbons	1.63E-4				
	brazing solder, cadmium free, at plant	RER	0	kg	8.76E-3	8.76E-3	1	1.13	(1,4,1,3,1,3); de Wild 2007, Sn60Pb40 plating on tabbing material, Sn plating on interconnect/terminal ribbons	8.76E-3		-		
	solar glass, low-iron, at regional storage	RER	0	kg	1.01E+1	1.01E+1	1	1.24	(1,4,1,3,3,3); de Wild 2007, 4mm thickness (3.2-4 mm for different producers), 1% losses, density 2.5 g/cm3	1.01E+1		1.15E+1		
	copper, at regional storage	RER	0	kg	1.13E-1	1.13E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, copper ribbons for cell interconnection	1.13E-1		5.48E-2		
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	1.88E-1	1.88E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, polyphenylenoxid for junction box	1.88E-1		-		
	ethylvinylacetate, foil, at plant	RER	0	kg	1.00E+0	1.00E+0	1	1.13	(1,4,1,3,1,3); de Wild 2007, EVA consumption 0.96 kg/m2, 6% more than glass area	1.00E+0		9.13E-1		
	polyvinylfluoride film, at plant	US	0	kg	1.10E-1	1.10E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, back foil, for solar cell module, 350 micron thickness: 2x37 micron polyvinyl fluoride, 250 micron polyethylene terephthalate; 0.488 g/m2, 7% cutting loss	1.10E-1		4.56E-2		
	polyethylene terephthalate, granulate, amorphous, at plant	RER	0	kg	3.73E-1	3.73E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, back foil, for solar cell module, 350 micron thickness: 2x37 micron polyvinyl fluoride, 250 micron polyethylene terephthalate; 0.488 g/m2, 7% cutting loss	3.73E-1		1.64E+0		
	silicone product, at plant	RER	0	kg	1.22E-1	1.22E-1	1	1.13	(1,4,1,3,1,3); de Wild 2007, kit to attach frame and junction box and for diaphragm of laminator	1.22E-1		3.42E-3		
auxiliary materials	acetone, liquid, at plant	RER	0	kg	1.30E-2	1.30E-2	1	1.13	(1,4,1,3,1,3); de Wild 2007, cleaning fluid	1.30E-2		3.61E-5		
	methanol, at regional storage	CH	0	kg	2.16E-3	2.16E-3	1	1.13	(1,4,1,3,1,3); GSS 2001, auxiliary material			2.16E-3		
	vinyl acetate, at plant	RER	0	kg	1.64E-3	1.64E-3	1	1.13	(1,4,1,3,1,3); GSS 2001, ethylacetat, auxiliary material			1.64E-3		
	lubricating oil, at plant	RER	0	kg	1.61E-3	1.61E-3	1	1.13	(1,4,1,3,1,3); GSS 2001, auxiliary material			1.61E-3		
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	1.10E+0	1.10E+0	1	1.13	(1,4,1,3,1,3); de Wild 2007, packaging estimation	1.10E+0		-		
	1-propanol, at plant	RER	0	kg	8.14E-3	8.14E-3	1	1.13	(1,4,1,3,1,3); de Wild 2007, soldering flux, 95% propanol	8.14E-3		1.10E-2		
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.35E+0	1.61E+0	1	2.09	(4,5,na,na,na,na); Standard distance 100km, cells 500km			-		
	transport, freight, rail	RER	0	tkm	7.87E+0	9.45E+0	1	2.09	(4,5,na,na,na,na); Standard distance 600km			-		
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	3.00E-2	1	1.13	(1,4,1,3,1,3); Alsema (personal communication) 2007, production waste	3.00E-2		8.22E-1		
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	1.10E-1	1.10E-1	1	1.13	(1,4,1,3,1,3); Calculation, including disposal of the panel after life time			-		
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	1.69E+0	1.69E+0	1	1.13	(1,4,1,3,1,3); Calculation, including disposal of the panel after life time	7.51E-2		-		
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.61E-3	1.61E-3	1	1.13	(1,4,1,3,1,3); Calculation, oil used during production			5.84E-3		
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	2.13E-2	2.13E-2	1	1.13	(1,4,1,3,1,3); Calculation, water use			-		
emission air	Heat, waste	-	-	MJ	1.70E+1	1.70E+1	1	1.29	(3,4,3,3,1,5); Calculation, electricity use			-		
												-		
	total weight			kg	12.0	14.6				14.7		16.6		
	Disposal			kg	1.8	1.8				0.1		0.8		

8.8 Infrastructure of panel and laminate production plant

The inventory includes the transformation and occupation of land as well as the buildings. Data were available for different production places (de Wild-Scholten & Alsema 2007; GSS 2001; Solar-Fabrik 2002). Tab. 8.3 shows the unit process raw data of the infrastructure of module production. The life-time of the factory is assumed with 25 years. It has an annual production capacity 10’000 solar modules of each 16kg.

Tab. 8.3 Unit process raw data of the infrastructure of module production. Lifetime 25 years, annual production capacity 10'000 solar modules of 16 kg each (de Wild-Scholten & Alsema 2007; GSS 2001; Solar-Fabrik 2002, www.wuerth-solar.de)

	Name	Location	Infrastr	Unit	photovoltaic panel factory	UncertaintyType	StandardDeviation	GeneralComment	GSS Ostthüringen	Solar-Fabrik	de Wild 2007	First Solar	Würth Solar, CIS
	Location				GLO				DE	DE	RER	US	DE
	InfrastructureProcess				1				1	1	1		
	Unit				unit				a	a	a	a	a
product	photovoltaic panel factory	GLO	1	unit	1.00E+0								
technosphere	building, hall	CH	1	m2	7.99E+2	1	3.00	(1,2,1,1,1,3); Environmental report	9.80E+2	4.26E+3	4.20E+3	1.86E+4	2.26E+4
	metal working machine, unspecified, at plant	RER	1	kg	4.00E+3	1	3.32	(5,5,1,1,1,5); rough assumption, 4t weight per laminator					
resource, land	Occupation, industrial area, built up	-	-	m2a	1.65E+4	1	1.51	(1,2,1,1,1,3); 25a occupation					
	Occupation, industrial area, vegetation	-	-	m2a	2.33E+4	1	1.51	(1,2,1,1,1,3); 25a occupation					
	Occupation, traffic area, road network	-	-	m2a	2.87E+3	1	1.51	(1,2,1,1,1,3); 25a occupation					
	Transformation, from unknown	-	-	m2	1.71E+3	1	2.00	(1,2,1,1,1,3); Environmental report, calculated	7.19E+3	6.88E+3			3.00E+4
	Transformation, to industrial area, built up	-	-	m2	6.59E+2	1	2.00	(1,2,1,1,1,3); Environmental report, weighted average for 5 companies	9.80E+2	4.26E+3	4.20E+3	1.86E+4	1.37E+4
	Transformation, to industrial area, vegetation	-	-	m2	9.33E+2	1	2.00	(1,2,1,1,1,3); Environmental report, weighted average for 3 companies	4.70E+3	2.62E+3			1.63E+4
	Transformation, to traffic area, road network	-	-	m2	1.15E+2	1	2.00	(1,2,1,1,1,3); Environmental report, weighted average for 2 companies	1.51E+3	-			
production	PV-panels			m2	1.00E+4				2.19E+4	1.10E+5	2.28E+5	1.52E+5	1.22E+5

8.9 Meta information of PV panel and laminate production

Tab. 8.4 show the EcoSpold meta information of PV panel and laminate production investigated in this chapter.

Tab. 8.4 EcoSpold meta information of PV panel and laminate production

ReferenceFunction	Name	photovoltaic laminate, single-Si, at plant	photovoltaic laminate, multi-Si, at plant	photovoltaic laminate, ribbon-Si, at plant	photovoltaic panel, single-Si, at plant	photovoltaic panel, multi-Si, at plant	photovoltaic panel, ribbon-Si, at plant
Geography	Location	RER	RER	RER	RER	RER	RER
ReferenceFuncti	InfrastructureProcess	1	1	1	1	1	1
ReferenceFuncti	Unit	m2	m2	m2	m2	m2	m2
	IncludedProcesses	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Aluminium frame of the panel. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Aluminium frame of the panel. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC	Production of the cell matrix, cutting of foils and washing of glass, production of laminate, isolation. Aluminium frame of the panel. Disposal after end of life. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC
	LocalName	Solarlaminat, single-Si, ab Werk	Solarlaminat, multi-Si, ab Werk	Solarlaminat, ribbon-Si, ab Werk	Solarpaneel, single-Si, ab Werk	Solarpaneel, multi-Si, ab Werk	Solarpaneel, ribbon-Si, ab Werk
	Synonyms	monocrystalline//single crystalline//silicon	polycrystalline//multi-crystalline//silicon	polycrystalline//multi-crystalline//silicon	Solarmodul//PV-module//monocrystalline//silicon	Solarmodul//PV-module//polycrystalline//multi-crystalline//silicon	Solarmodul//PV-module//polycrystalline//multi-crystalline//silicon
	GeneralComment	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 224 Wp. Cell size and amount and capacity might differ between different producers.	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 210Wp. Cell size and amount and capacity might differ between different producers.	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 192 Wp. Cell size and amount and capacity might differ between different producers.	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 224 Wp. Cell size and amount and capacity might differ between different producers.	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 210Wp. Cell size and amount and capacity might differ between different producers.	Unit process raw data for 1 m2 of PV panel. Investigated for the production of solar panels and laminates with 60 solar cells a 156*156cm2 with a capacity of 192 Wp. Cell size and amount and capacity might differ between different producers.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components	production of components	production of components	production of components
	Formula						
	StatisticalClassification						
	CASNumber						
TimePeriod	StartDate	2005	2005	2005	2005	2005	2005
	EndDate	2005	2005	2005	2005	2005	2005
	OtherPeriodText	Date of data investigation. Some older data from 2001.	Date of data investigation. Some older data from 2001.	Date of data investigation. Some older data from 2001.	Date of data investigation. Some older data from 2001.	Date of data investigation. Some older data from 2001.	Date of data investigation. Some older data from 2001.
Geography	Text	Production plants in Western Europe.	Production plants in Western Europe.	Production plants in Western Europe.	Production plants in Western Europe.	Production plants in Western Europe.	Production plants in Western Europe.
Technology	Text	Modern production plant.	Modern production plant.	Modern production plant.	Modern production plant.	Modern production plant.	Modern production plant.
Representativen	Percent	5	5	5	5	5	5
	ProductionVolume	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).	Worldwide module production in 2005, 1500MWp (60%mc-Si, 40% sc-Si).
	SamplingProcedure	Environmental reports, direct contacts with factory representatives and publication of plant data.	Environmental reports, direct contacts with factory representatives and publication of plant data.	Environmental reports, direct contacts with factory representatives and publication of plant data.	Environmental reports, direct contacts with factory representatives and publication of plant data.	Environmental reports, direct contacts with factory representatives and publication of plant data.	Environmental reports, direct contacts with factory representatives and publication of plant data.
	Extrapolations	Assumption for laminate production with data for panels. Materials for frames neglected.	Assumption for laminate production with data for panels. Materials for frames neglected.	Assumption for laminate production with data for panels. Materials for frames neglected.	Rough assumption for the use of heat in the process.	Rough assumption for the use of heat in the process.	Rough assumption for the use of heat in the process.

9 Thin film cells, laminates, and panels

9.1 Introduction

Thin film photovoltaic modules are so far only produced by a limited number of companies. Tab. 9.1 shows an overview of companies and production projects (Fawer 2006; Mints 2008),). It is expected that the production capacities are increasing considerably in the next years.

Tab. 9.1 Thin film companies and production projects (Fawer 2006; Mints 2008),

Company	Technology	Efficiency	Shipments (MWp) 2007	(Planned) Capacity (MWp) 2007
Antec (DE)	CdTe		2.5	25
Arendi (IT)	CdTe			15
Ascent Solar (USA)	CIGS			1.5
Avancis (GB/FR)	CIS	13.5%		20
CSG Solar (DE)	aSi		2.7	
DayStarTechnologies (USA)	CIGS	10.0%		20
ErSol Thin Film (DE)	aSi	10.0%		40
First Solar (USA/DE)	CdTe		186.0	240
Honda (JP)	CIGS		6.9	27
Johanna Solar (DE)	CIGSSe	16.0%		30
Kaneka (JP)	aSi		35.0	47
Mitsubishi Heavy Industries (JP)	aSi	11.5%	14.0	40
Nanosolar (USA)	CIGS	10.0%		430
Odersun (DE)	CIS	10.0%		4.5
Sanyo (JP)	aSi		5.0	
Schott Solar (DE)	aSi		4.0	30
Sharp (JP)	aSi/Tandem		10.0	
Shenzen Topray Solar (CN)	aSi			15
Sinonar (CN)	aSi		3.0	
Solar Cells	aSi		2.0	
Sulfurcell (DE)	CIS with sulphur			50
United Solar Systems (USA)	aSi		48.0	60
Würth Solar (DE)	CIS	11.0%	10.0	15
others			7.1	
Total			**330**	**>1130**

9.2 Cadmium telluride photovoltaic laminates (CdTe)

9.2.1 Introduction

The theoretical benefits of CdTe and other thin film technologies have long been recognized. The unique physical properties of CdTe make it useful for converting solar energy into useful electricity. First Solar describes the specific advantages as follows:[24]

- CdTe is a direct bandgap semiconductor. The energy bandgap of CdTe, at 1.45ev, enables it to convert more energy from the solar spectrum (i.e., more watts per kg of material) than the lower

[24] Company information provided on www.firstsolar.com (2006).

energy bandgap materials (1.20ev) used historically. As a result, CdTe is capable of converting solar energy into electricity at an efficiency rate comparable to historical technologies with about 1% of the semiconductor material requirement.

- Solar cells become less efficient at converting solar energy into electricity as their cell temperatures increase. However, the efficiency of CdTe is less susceptible to cell temperature increases, enabling CdTe solar modules to generate relatively more electricity under high ambient (and therefore high cell) temperatures. CdTe also absorbs low and diffuse light and more efficiently converts it to electricity under cloudy weather and dawn and dusk conditions where conventional cells operate less efficiently.
- The robustness of CdTe enables relatively simple device structures and production processes. High performance modules are achieved with single junction, multicrystalline devices. Automated high throughput production processes have been employed successfully with CdTe, without the need for expensive clean rooms or other expensive specialty equipment.
- Transforming cadmium and tellurium into a stable, inert semiconductor makes CdTe. Both elemental materials are produced as by-products of mining processes (primarily zinc mining and copper refining) and available in abundant quantities to support annual production of several GWp.

We investigate CdTe technology with the available data from the United States (US) and Germany (DE). Data for the necessary coating materials are investigated in a separate report (Classen et al. 2007).

9.2.2 Characterisation of the product

Cadmium telluride photovoltaic modules are so far only produced by a limited number of companies (see Tab. 9.1).

First Solar[25]

The laminates produced by First solar have a size of 1.2 m by 0.6 m. The weight is 12 kg. The average efficiency over the life time is 9%. The company sells different laminates with efficiencies of 8.3% to 10.8%. The rated nominal power is about 65Wp per laminate.

The First Solar laminate is comprised of the materials shown in Fig. 9.1. The semiconductor materials (CdTe and CdS) originate from by-products of mining operations. First Solar laminates incorporate only small amounts of semiconductor material.

[25] Company information provided on www.firstsolar.com (2008).

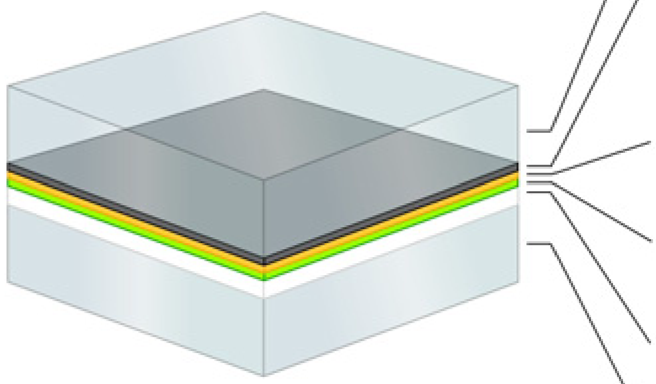


Fig. 9.1 Materials used for the First Solar laminates (www.firstsolar.com)

9.2.3 Production process

The technology used to deposit the semiconductors on the First Solar laminates is vapour transport deposition (VTD). It relies on the sublimation of the powders and condensation of the vapours on a glass substrate (Fthenakis & Kim 2005). The module processing includes film deposition, etching, cleaning, and module assembly.

9.2.4 Life cycle inventories of cadmium telluride solar laminates

The life cycle inventory data of this technology are based on the following publication:

- Detailed and most recent investigation by Fthenakis and colleagues for the production process at **First Solar, US** (Fthenakis 2004; Fthenakis & Kim 2005). The authors of these articles provided further detailed information, which is the main basis for this life cycle inventory. Technical data for single modules were available on the homepage (www.firstsolar.de). Some earlier data for the Cd emissions and wastes by this producer are provided by Bohland & Smigielski (2000).

In previous reports, data from an investigation of Raugei et al. (2006) were applied. However, since the corresponding facility stopped its production, these data are no considered any more and the inventory data are based only on informations from First Solar.

Production in the United States

The unit process raw data for the production in the United States are presented in Tab. 9.2. Most inventory data for the production at First solar in the US are based on the information provided in a detailed EXCEL file provided by Prof. Fthenakis to the authors. This was also the basis for the two publications mentioned before. Data for the use of most coating materials were available, except detailed data for the composition of some cadmium compounds. According to the authors the following items are included in the analysis (Fthenakis & Kim 2005; Fthenakis & Alsema 2006):

- Electricity - Electricity demand is the most significant energy usage during the module manufacturing. Module processing, overhead operations and office use are the main contributors to electricity demand. Module processing includes film deposition, etching, cleaning, and module assembly while overhead operations include environmental control, lightening, health, and safety controls.

- Chemicals – Chemicals are used during the manufacturing process for cleaning, etching, and waste treatment during operation and maintenance; these include sulphuric acid, nitric acid, isopropyl alcohol, sodium hydroxide, and glass cleaners.
- Consumables – Consumables used in the CdTe manufacturing facility include production supplies, repair and maintenance supplies, and safety supplies. Major production supplies include wires, welding rods, and filters while repair and maintenance supplies include cables, cable ties, bolts, nuts, screws, and washers. Safety supplies include goggles, protection gears, and gloves. Around 400 consumable items are included in this analysis in a summarized form based on background data from the US input-output table.
- Water Use – Water use during the manufacturing process is associated with glass/substrate and module cleaning, chemical solutions, and laboratory uses.

The disposal of production wastes is not known. It has been assessed with data from a module producer (GSS 2001), which have also been used for other types of panels (Tab. 8.2). All used water is assumed to be treated as wastewater. Data for the treatment of glass production effluents are used as a proxy as the main process is similar to other processes used in glass coating.

The emission of cadmium to air has been estimated with published data (Fthenakis 2004). The amount of other emissions from the process is not known.

The infrastructure of the production facilities is modelled on the generic data used in this study. Own assumptions have been used for calculating transport of materials.

Production in Germany

In 2007 First Solar opened a new factory in Germany, producing cadmium telluride laminates showing the same production efficiency as the one in the US.[26] Therefore, the same inventory data are applied as for the production in the US, however, with country-specific electricity mix.

[26] Personal communication with L. Krueger, First Solar, 18.11.08.

Tab. 9.2 Unit process raw data of cadmium telluride solar laminates production in the United States and Germany, as well as literature data

	3702	3703	##	3706	3707	3707	#	3709	3792	Fthenakis 2005, Excel File	Fthenakis 2005	Fthenakis 2004	Fthenakis 2004	Bohland 2000
	Name	Location	InfrastructureProcess	Unit	photovoltaic laminate, CdTe, at plant	photovoltaic laminate, CdTe, at plant	UncertaintyType	StandardDeviation95%	GeneralComment	*CdTe cell, First Solar*	*CdTe Module, First Solar*	*CdTe Module, Electrochemical deposition*	*CdTe Module, vapour deposition*	*CdTe Module, First Solar*
	Location				US	DE				*US*	*US*	*US*	*US*	*US*
	InfrastructureProcess				1	1								
	Unit				m2	m2				*m2*	*m2*	*m2*	*m2*	*m2*
product	photovoltaic laminate, CdTe, at plant	US	1	m2	1.00E+0	-								
	photovoltaic laminate, CdTe, at plant	DE	1	m2	-	1.00E+0								
technosphere	electricity, medium voltage, at grid	US	0	kWh	5.81E+1	-	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	5.81E+1	5.86E+1			
	electricity, medium voltage, at grid	DE	0	kWh	-	5.81E+1	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	5.81E+1	5.86E+1			
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	4.00E-6	1	3.03	(3,4,2,1,1,3); Assumption					
water	tap water, at user	RER	0	kg	2.19E+2	2.19E+2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	2.19E+2				
processing	tempering, flat glass	RER	0	kg	9.15E+0	9.15E+0	1	1.08	(1,2,2,1,1,3); amount of flat glass tempered	9.15E+0				
materials	copper, at regional storage	RER	0	kg	5.18E-1	5.18E-1	1	1.08	(1,2,2,1,1,3); Fthenakis, including metal compounds for coating and contacts	5.18E-1	x			
	lead, at regional storage	RER	0	kg	7.08E-4	7.08E-4	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	7.08E-4				
	silicone product, at plant	RER	0	kg	3.07E-3	3.07E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	3.07E-3				
	steel, low-alloyed, at plant	RER	0	kg	2.20E-1	2.20E-1	1	1.08	(1,2,2,1,1,3); Fthenakis, literature		2.20E-1			
	solar glass, low-iron, at regional storage	RER	0	kg	1.92E+1	1.92E+1	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	1.92E+1	2.18E+1			
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	1.08E-1	1.08E-1	1	1.08	(1,2,2,1,1,3); Fthenakis, literature, sum up of several materials	1.08E-1				
	ethylvinylacetate, foil, at plant	RER	0	kg	6.00E-1	6.00E-1	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	6.00E-1				
coating	aluminium, primary, at plant	RER	0	kg	1.50E-2	1.50E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	1.50E-2	x			
	chromium, at regional storage	RER	0	kg	3.15E-3	3.15E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	3.15E-3	x			
	cadmium telluride, semiconductor-grade, at plant	US	0	kg	4.34E-2	4.34E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature, incl. Part of Cd compound powder	4.34E-2	x	7.92E-3	3.35E-2	
	cadmium sulphide, semiconductor-grade, at plant	US	0	kg	3.52E-3	3.52E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature, incl. Part of Cd compound powder	3.52E-3	6.50E-2	1.04E-2	1.80E-3	
	tin, at regional storage	RER	0	kg	-	-	1	1.08	(1,2,2,1,1,3); Not used	-	x		*2.97E-2*	
auxiliary materials	acetone, liquid, at plant	RER	0	kg	8.91E-3	8.91E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	8.91E-3	8.50E-1			
	nitric acid, 50% in H2O, at plant	RER	0	kg	5.72E-2	5.72E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	5.72E-2	x			
	sulphuric acid, liquid, at plant	RER	0	kg	3.93E-2	3.93E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	3.93E-2	x			
	silica sand, at plant	DE	0	kg	4.68E-2	4.68E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	4.68E-2				
	sodium chloride, powder, at plant	RER	0	kg	4.53E-2	4.53E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	4.53E-2				
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	1.67E-2	1.67E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	1.67E-2				
	soda, powder, at plant	RER	0	kg	1.51E-2	1.51E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	1.51E-2				
	isopropanol, at plant	RER	0	kg	2.08E-3	2.08E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	2.08E-3	x			
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	4.93E-2	4.93E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	4.93E-2	x			
	chemicals inorganic, at plant	GLO	0	kg	3.50E-2	3.50E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature, sum up of several chemicals	3.50E-2				
	chemicals organic, at plant	GLO	0	kg	9.74E-3	9.74E-3	1	1.08	(1,2,2,1,1,3); Fthenakis, literature, sum up of several chemicals	9.74E-3				
	nitrogen, liquid, at plant	RER	0	kg	7.32E-2	7.32E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	7.32E-2				
	helium, gaseous, at plant	RER	0	kg	3.64E-2	3.64E-2	1	1.08	(1,2,2,1,1,3); Fthenakis, literature	3.64E-2				
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	1.37E+0	1.37E+0	1	1.08	(1,2,2,1,1,3); Fthenakis, packaging material	1.37E+0				
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.35E+1	1.35E+1	1	2.01	(1,2,2,1,1,3); Average distance 600km, Fthenakis		0.15l fuel oil			
	transport, freight, rail	RER	0	tkm	1.35E+1	1.35E+1	1	2.09	(4,5,na,na,na,na); Average distance 600km					
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	3.00E-2	1	1.13	(1,4,2,3,1,3); Alsema (personal communication) 2007, production waste					
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	7.08E-1	7.08E-1	1	1.08	(1,2,2,1,1,3); Calculation					
	treatment, glass production effluent, to wastewater treatment, class 2	CH	0	m3	2.19E-1	2.19E-1	1	1.08	(1,2,2,1,1,3); Calculation					
emission air	Heat, waste	-	-	MJ	2.09E+2	2.09E+2	1	1.29	(3,4,3,3,1,5); Calculation					
	Cadmium	-	-	kg	2.10E-8	2.10E-8	1	5.05	(4,1,2,1,1,na); Literature data and own assumption for share of different inputs		2.10E-8		1.00E-7	1.00E-9
	total weight of used materials			kg	22.5	22.5			including chemicals, packaging, losses, etc.	22.3	22.9	0.0	0.065	0.0
	disposal			kg	0.03	0.03				0.1	0.1	0.0	0.0	0.0
	laminate materials			kg	20.7	20.7			including losses	16.7	15.8	0.0	0.1	0.0

x Materials are known to be used, but only sum of masses provided in the publication. Frames used to highlight the amounts partly disaggregated or to highlight to which materials a summarized sum refers to

Production mix

According to Mints (2008), First Solar produced 76.0 MW of cadmium telluride laminates in Europe and 110.0 MW in the US in 2007, which are all installed in Europe.[27] Therefore, the production mix for photovoltaic CdTe modules used in Europe has been assessed with a share of 59 % for imports from the US and 41 % from production in Germany. For imported laminates a transport distance of 6300 km by ship has been assumed. In addition for both types a transport distance to a regional storage of 200 km by rail and 50 km by lorry has been adopted.

[27] Personal communication with L. Krueger, First Solar, 19.11.08: "First Solar does not report country specific sale numbers; however for purposes of this analysis it is reasonable to assume that 100 % of First Solar shipments were installed in Europe."

Tab. 9.3 Unit process raw data of cadmium telluride solar laminates production mix in Europe (RER)

	Name	Location	InfrastructureProcess	Unit	photovoltaic laminate, CdTe, mix, at regional storage	UncertaintyType	StandardDeviation95%	GeneralComment	
	Location				RER				
	InfrastructureProcess				1				
	Unit				m2				
	photovoltaic laminate, CdTe, mix, at regional storage	RER	1	m2	1.00E+0				
modules	photovoltaic laminate, CdTe, at plant	US	1	m2	5.90E-1	1	1.53	(5,4,1,1,1,3); 2007 share of First Solar production in the US	59%
modules	photovoltaic laminate, CdTe, at plant	DE	1	m2	4.10E-1	1	1.53	(5,4,1,1,1,3); 2007 share of First Solar production in Germany	41%
transport	transport, transoceanic freight ship	OCE	0	tkm	7.65E+1	1	2.09	(4,5,na,na,na,na); Import of modules from the US 6300km	
	transport, freight, rail	RER	0	tkm	4.14E+0	1	2.09	(4,5,na,na,na,na); Standard distance 200km	
	transport, lorry >16t, fleet average	RER	0	tkm	1.04E+0	1	2.09	(4,5,na,na,na,na); Standard distance 50km	

Meta information of CdTe solar laminates

Tab. 9.4 EcoSpold meta information of cadmium telluride solar modules

ReferenceFunction	Name	photovoltaic laminate, CdTe, at plant	photovoltaic laminate, CdTe, at plant	photovoltaic laminate, CdTe, mix, at regional storage
Geography	Location	US	DE	RER
ReferenceFuncti	InfrastructureProcess	1	1	1
ReferenceFuncti	Unit	m2	m2	m2
	IncludedProcesses	Electricity including overhead operations and office use, materials, transport of materials, infrastructure. Module processing includes film deposition, etching, cleaning and module assembly. Disposal after end of life. Process emissions not known (except Cd).	Electricity including overhead operations and office use, materials, transport of materials, infrastructure. Module processing includes film deposition, etching, cleaning and module assembly. Disposal after end of life. Process emissions not known (except Cd).	Production mix for use in Europe. Transport of modules from overseas.
	LocalName	Solarlaminat, CdTe, ab Werk	Solarlaminat, CdTe, ab Werk	Solarlaminat, CdTe, Mix, ab Regionallager
	Synonyms	Solarmodul//PV-module//cadmium telluride//thin film//ATF/advanced thin film	Solarmodul//PV-module//cadmium telluride//thin film//ATF/advanced thin film	Solarmodul//PV-module//cadmium telluride//thin film
	GeneralComment	Production of photovoltaic thin film modules by vapour deposition. The modules produced at First Solar have a size of 1.2m by 0.6 m. The weight is 12.0kg. The efficiency is 9%. The rated nominal power is about 65Wp per module.	Production of photovoltaic thin film modules by vapour deposition. The modules produced at First Solar have a size of 1.2m by 0.6 m. The weight is 12.0kg. The efficiency is 9%. The rated nominal power is about 65Wp per module.	Estimation for new type of photovoltaic thin film modules used in Europe based on 41% German production and 59% US production. Average efficiency is 9.0%.
	Category	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components
	Formula			
	StatisticalClassification			
	CASNumber			
TimePeriod	StartDate	2004	2004	2004
	EndDate	2005	2005	2007/2008
	OtherPeriodText	Data published in 2004 - 2005.	Data published in 2004 - 2005.	Data refer to 2008. Production in 2007 was estimated.
Geography	Text	Data for First Solar in US.	Data for First Solar in Germany.	Production sites in DE and US. Estimation for share of products on European market.
Technology	Text	Production technology of thin film cells. Sublimation of the powders and condensation of the vapours on a glass substrate by vapour transport deposition (VTD).	Production technology of thin film cells. Sublimation of the powders and condensation of the vapours on a glass substrate by vapour transport deposition (VTD).	none
Representativen	Percent	100	100	100
	ProductionVolume	110.0 MW in 2007	76.0 MWp in 2007	30 MWp in 2006
	SamplingProcedure	Literature data based on producer information.	Literature data based on producer information.	Literature data on worldwide CdTe module production.
	Extrapolations	Waste disposal from factory approximated with data for crystalline modules. The quantity of several small material uses (about 700 items) has been summarized for some main materials.	The same inventory data are applied as for the production in the US, however, with country-specific electricity mix. Waste disposal from factory guesstimated with data for crystalline modules. The quantity of several small material uses (about 700 items) has been summarized for some main materials.	Market share calculation based on literature data .

9.3 Copper indium selenide photovoltaic panels (CIS)

9.3.1 Introduction

The term CIS is an abbreviation for a chemical compound. This comprises the starting letters of the elements forming this material compound, e.g. copper indium selenide: C – Cu (copper), I – indium, S – selenium. Another expression that is used sometimes for this type of technology is CIGS were the G stands for gallium. The thin film CIS technology is investigated here with data from Würth Solar in Germany and with published articles. The following descriptions in this chapter have mainly been found on the homepage of Würth Solar (www.wuerth-solar.de).

9.3.2 Reserves and resources of material

Materials with a structure and composition, in which two or three metals (e.g. copper, zinc or iron) are combined with selenium, sulphur or tellurium, occur abundantly in nature as ore minerals. The elements selenium, sulphur and tellurium are therefore also known as chalcogens and the compounds with the metals are termed chalcogenides. As a result of its crystalline structure, CIS, with the chemical formula CuInSe2, belongs to the family of chalcopyrites.

Because the CIS compounds readily absorb sunlight (this is apparent from their deep black appearance), wafer thin layers are sufficient to completely absorb incident sunlight and to partially convert light into electrical current.

One speaks of a CIS (thin film) solar cell based on the CIS compound semiconductor, if this photovoltaic active layer of 1 to 2 μm thickness is embedded between layers of partially transparent, but conductive and similarly thin electrode layers.

The companies shown in Tab. 9.1 are active in producing CIS-modules.

9.3.3 Characterisation of the product

Fig. 9.2 shows the different layers of a CIS thin film cell.[28] The active layer consists of a specific copper-indium-selenium (CuInSe2) configuration and is deposited with a vaporization process directly over a large area of the substrate material (window glass). This layer is just a few micrometers (1/1000 mm) thick.

Large-area deposition techniques, such as thermal vaporization in vacuum, are suitable for production. These and other techniques (sputtering in the technical jargon) for the production of thin layers are similar to those used in the modern glass industry for the manufacture of heat reflecting surfaces.

As in the glass industry, cheap window glass produced in large quantities can be used as a substrate for CIS solar modules. The required sequence of layers is deposited in the various subsequent production steps.

The cells are then separated and electrically connected together with the respective structuring steps. The result is a module with a higher operating voltage corresponding to that of the constituent cells. In the case of thin layer solar cells, this serial connection – also known as integration – can be carried out during the production process. This configuration is normally hermetically sealed with a second glass plate, the cover glass plate.

The modules produced at Würth solar have a size of 1.2m by 0.6m. The weight is 12.6kg. The efficiency is 10%. The rated nominal power is about 75-80Wp per module.

[28] Information provided on www.wuerth-solar.de (2006).

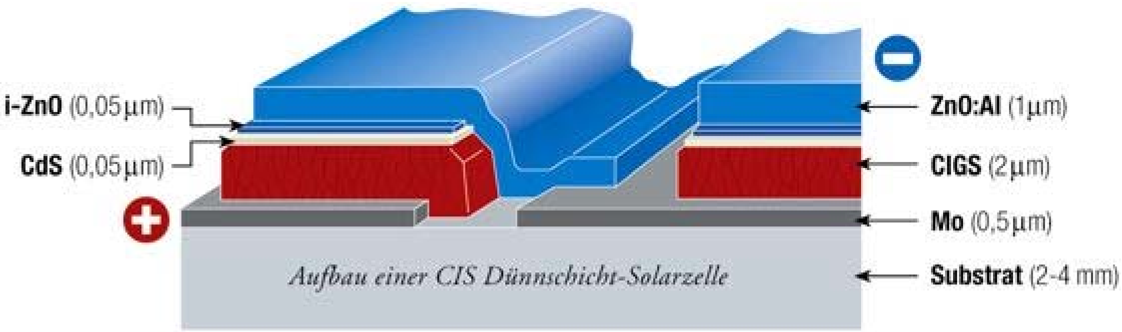


Fig. 9.2 Principal materials of a CIS thin film solar cell (www.wuerth-solar.de).

9.3.4 Production process

Fig. 9.3 shows the production process at Würth Solar.

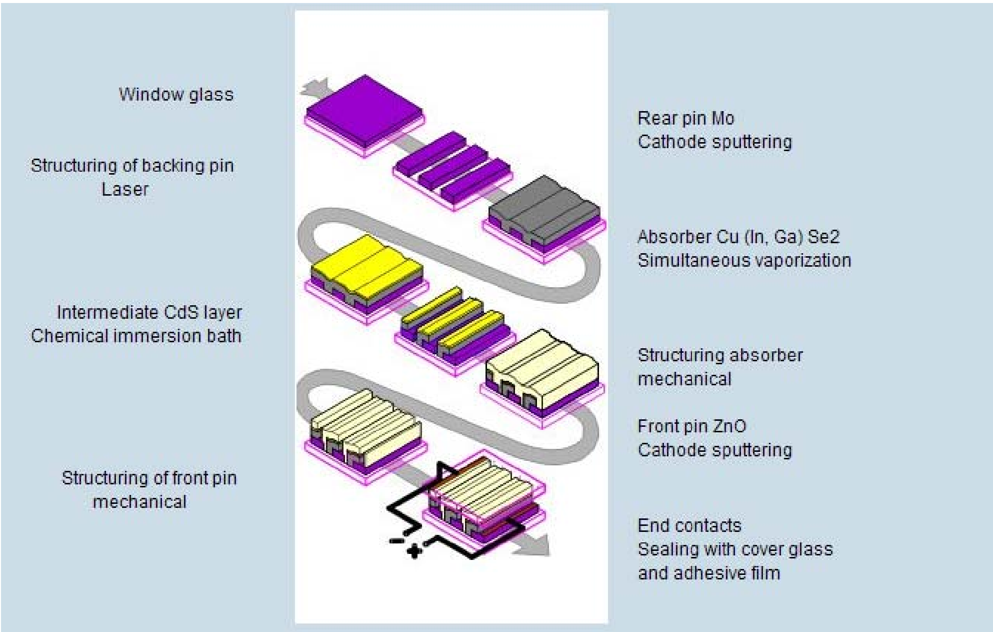


Fig. 9.3 Production process at Würth solar for CIS thin film solar cell (www.wuerth-solar.de).

9.3.5 Life cycle inventories of CIS laminates and panels

The following information and publications have been used to elaborate the life cycle inventory analysis of copper-indium-diselenide (CIS) PV modules:

- Data are mainly available for the production process of Würth Solar in Germany. The company provided key figures on energy and material inputs as well as wastes for the production in 2007 in a personal communication.[29] Some data are shown for the production process at Würth Solar directly on the company's homepage (www.wuerth-solar.de).
- An updated life cycle assessment of modules produced at **Würth Solar** has been investigated in

[29] Personal communication with Bernhard Dimmler, Würth Solar, 27.2.2007 and Tobias Brosi, Würth Solar, 13.3.2007.

the SENSE project[30]. The data are so far confidential and were not available for this report.

- Older data have been published in an article by Raugei et al. (2006) based on a former work (Raugei 2005). However, that work investigated the production of very specific designer modules and is thus not representative for the production of average modules today.
- An earlier work investigated data for the producer Siemens (now Shell Solar) (Ampenberger et al. 1998). These data have also been evaluated.
- Further information was available from literature (Naujoks 2000) for the producer Sulfurcell. This has been used to verify some results, but it was not possible to derive life cycle inventory data from this publication.
- The production process of Shell Solar Europe has been described in a publication (Briem et al. 2004). No inventory data are published for this process. The cumulative energy demand for the module is calculated as 32.7 GJ for 3.12 kW_p or 1253 MJ/m^2 of panel. The new producers name is Avancis.
- A publication from the US investigated the pilot plant production at Siemens Solar Industries (now Shell Solar) (Knapp & Jester 2000a; b).

The available literature data are shown in Tab. 9.5. The life cycle inventory for CIS-modules is shown in Tab. 9.6. A summary description of the investigated process and the quality of data can be found in Tab. 9.7.

The life cycle inventory is based mainly on the information directly provided by the company. Recent literature data (Raugei 2005; Raugei et al. 2006) have been used for verification. The information provided in an older study for the amount of different coating materials has been used to estimate the share of different materials (Ampenberger et al. 1998).

Electricity is not only used for the operation of production machines, but also air-conditioning, water-purification, etc. The data for the electricity use range between 17 and 236[31] kWh/m^2 of laminated glass (Ampenberger et al. 1998; Knapp & Jester 2000a; b; Raugei 2005; Raugei et al. 2006). Here we use information provided by the company and estimate the total electricity use for coating, air-conditioning, water purification, etc. with 122 kWh/m^2.

According to the company information, the amount of tap water is slightly higher than the discharge of water. Data for the treatment of glass production effluents are used as a proxy as the main process is similar to other processes used in glass coating.

Further data for auxiliary materials used in the production process have been investigated by Ampenberger et al (1998) because more recent data were not available.

Emission data for this specific process were not available. The possible emission of cadmium to air has been estimated using (Fthenakis & Kim 2005) as a worst-case assumption, but it has to be noted that these data refer to another type of process. The amount of other emissions from the process is not known.

The modules are packed in returnable boxes. The related material is not considered in the unit process

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[30] www.sense-eu.net (2006).

[31] Personal communication with M. Raugei, 15.12.06: We are aware that the data for the electricity use per module may have been wrongly calculated as the gross electricity use of the factory divided by the number of modules produced. This would result in an overestimate, of course, especially considering that at the time of the investigation the production facility was still in a pilot production stage (as noted in our paper) and there was still a fair amount of inevitable wasteful energy consumption going on. As regards the issues of glass and water use, I cannot be very precise at the moment, but I recall that glass was calculated based on an assumption consistent with the currently (2004) available literature rather than on direct input by the manufacturer.

raw data.

Tab. 9.5 Literature data of CIS laminates and modules (Source in the first raw). Life cycle inventory data can be found in Tab. 9.6

	3702	3703	##	3706	Würth Solar 2007	Raugei 2007	Raugei 2006	Knapp 2000	Ampenberger 1998	Ampenberger 1998	Ampenberger 1998	Ampenber ger 1998	own assumption
	Name	Location	InfrastructureProcess	Unit	*CIS, cells, Würth Solar*	*CIS, cells, Würth Solar*	*CIS, BOS module*	*CIS module*	*CIS Module, large, 50 bzw. 56 Wpeak*	*CIS Module, large, 50 bzw. 56 Wpeak*	*CIS Module, Pilot, 50 bzw. 56 Wpeak*	*CIS Module, 50 bzw. 56 Wpeak*	*share of coating materials*
	Location				*DE*	*DE*	*DE*	*US*	*DE*	*DE*	*DE*	*DE*	
	InfrastructureProcess												
	Unit				*m2*	*m2*	*m2*	*m2*	*m2*	*0.51 m2*	*0.51 m2*	*%*	*%*
product	photovoltaic laminate, CIS, at plant	DE	1	m2									
	photovoltaic panel, CIS, at plant	DE	1	m2									
technosphere	electricity, medium voltage, at grid	DE	0	kWh	1.22E+2	2.36E+2		1.61E+1	3.93E+1	2.00E+1			
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-		1.08E+1	to	4.09E+1	2.09E+1			
infrastructure	photovoltaic panel factory	GLO	1	unit	-			1.41E+2					
	tap water, at user	RER	0	kg	2.67E+0	1.25E+0			1.67E+2	8.52E+1	9.83E+1		
	tempering, flat glass	RER	0	kg	-								
materials	photovoltaic laminate, CIS, at plant	DE	1	m2	-								
	aluminium alloy, AlMg3, at plant	RER	0	kg	1.57E+0		1.90E+0	7.28E+0					
	copper, at regional storage	RER	0	kg	4.50E-2		4.00E-2		6.67E-3	3.40E-3	4.90E-3	10%	
coating	molybdenum, at regional storage	RER	0	kg	9.55E-2	7.00E-2			7.25E-3	3.70E-3	7.60E-3	11%	11%
	indium, at regional storage	RER	0	kg	x	x			3.53E-3	1.80E-3	3.70E-3	5%	6%
	gallium, semiconductor-grade, at regional storage	RER	0	kg	x	x			-			0%	11%
	selenium, at plant	RER	0	kg	x	x			9.22E-3	4.70E-3	6.00E-3	14%	11%
	cadmium sulphide, semiconductor-grade, at plant	US	0	kg	x	x			3.92E-2	2.00E-2	3.12E-2	58%	36%
	zinc, primary, at regional storage	RER	0	kg	x	x			8.04E-3	4.10E-3	8.30E-3	12%	13%
	tin, at regional storage	RER	0	kg	x	x			-			0%	11%
	solar glass, low-iron, at regional storage	RER	0	kg	1.50E+1	2.50E+1			1.04E+1	5.30E+0	5.60E+0		
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	-		4.00E-2		-				
	ethylvinylacetate, foil, at plant	RER	0	kg	8.68E-1	8.77E-1		5.49E-1	8.82E-1	4.50E-1	5.80E-1		
auxiliaries	acetone, liquid, at plant	RER	0	kg	-				1.18E-2	6.00E-3	9.00E-3		
	argon, liquid, at plant	RER	0	kg	7.20E-3				1.71E-2	8.70E-3	6.17E-2		
	nitrogen, liquid, at plant	RER	0	kg	2.78E+0				6.67E-2	3.40E-2			
	ammonia, liquid, at regional storehouse	RER	0	kg	2.93E-1				5.69E-1	2.90E-1	5.00E-1		
	urea, as N, at regional storehouse	RER	0	kg	-				1.25E-1	6.39E-2	9.85E-2		
transport	transport, lorry >16t, fleet average	RER	0	tkm	-								
	transport, freight, rail	RER	0	tkm	-								
disposal	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	3.44E-2								
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	-								
	treatment, glass production effluent, to wastewater treatment, class 2	CH	0	m3	2.63E-3								
emission air	Heat, waste	-	-	MJ	-								
	Cadmium	-	-	kg	-								
	module materials			kg	20.7	25.9	2.0	7.8	12.1	6.2	6.9		17.6
	disposal			kg	0.0	0.0	0.0						1.0

x Materials are known to be used, but only sum of masses provided in the publication. Frames used to highlight the amounts partly disaggregated or to highlight to which materials a summarized sum refers to

Tab. 9.6 Unit process raw data for CIS laminates and modules

	Name	Location	InfrastructureProcess	Unit	photovoltaic laminate, CIS, at plant	photovoltaic panel, CIS, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE	DE			
	InfrastructureProcess				1	1			
	Unit				m2	m2			
product	photovoltaic laminate, CIS, at plant	DE	1	m2	1.00E+0	0			
	photovoltaic panel, CIS, at plant	DE	1	m2	0	1.00E+0			
technosphere	electricity, medium voltage, at grid	DE	0	kWh	1.22E+2	-	1	1.07	(1,1,1,1,1,3); company information, coating, air-conditioning, water purification, etc.
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-	1.08E+1	1	1.07	(1,1,1,1,1,3); Raugei, literature
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	-	1	3.02	(1,4,1,3,1,3); Assumption
	tap water, at user	RER	0	kg	2.67E+0	-	1	1.07	(1,1,1,1,1,3); company information
	tempering, flat glass	RER	0	kg	1.50E+1	-	1	1.07	(1,1,1,1,1,3); Assumption
materials	photovoltaic laminate, CIS, at plant	DE	1	m2	-	1.00E+0	1	1.07	(1,1,1,1,1,3); Assumption
	aluminium alloy, AlMg3, at plant	RER	0	kg	-	1.57E+0	1	1.07	(1,1,1,1,1,3); company information
	copper, at regional storage	RER	0	kg	4.50E-2	-	1	1.07	(1,1,1,1,1,3); company information
coating	molybdenum, at regional storage	RER	0	kg	1.10E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	indium, at regional storage	RER	0	kg	5.49E-3	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	gallium, semiconductor-grade, at regional storage	RER	0	kg	1.10E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	selenium, at plant	RER	0	kg	1.10E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	cadmium sulphide, semiconductor-grade, at plant	US	0	kg	3.40E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	zinc, primary, at regional storage	RER	0	kg	1.21E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	tin, at regional storage	RER	0	kg	1.10E-2	-	1	1.13	(3,2,2,1,1,3); company information and assumption for share of metals
	solar glass, low-iron, at regional storage	RER	0	kg	1.50E+1	-	1	1.07	(1,1,1,1,1,3); company information
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	-	4.00E-2	1	1.07	(1,1,1,1,1,3); Raugei, literature
	ethylvinylacetate, foil, at plant	RER	0	kg	8.68E-1	-	1	1.07	(1,1,1,1,1,3); company information
auxiliaries	acetone, liquid, at plant	RER	0	kg	1.18E-2	-	1	1.16	(3,1,3,1,1,3); Cleaning agent, Ampenberg 1998
	argon, liquid, at plant	RER	0	kg	7.20E-3	-	1	1.07	(1,1,1,1,1,3); protection gas, company information
	nitrogen, liquid, at plant	RER	0	kg	2.78E+0	-	1	1.07	(1,1,1,1,1,3); protection gas, company information
	ammonia, liquid, at regional storehouse	RER	0	kg	2.93E-1	-	1	1.07	(1,1,1,1,1,3); dip coating for CdS, company information
	urea, as N, at regional storehouse	RER	0	kg	1.25E-1	-	1	1.16	(3,1,3,1,1,3); dip coating for CdS, Ampenberg 1998
transport	transport, lorry >16t, fleet average	RER	0	tkm	1.94E+0	1.62E-1	1	2.09	(4,5,na,na,na,na); Standard distance 100km
	transport, freight, rail	RER	0	tkm	1.15E+1	9.66E-1	1	2.09	(4,5,na,na,na,na); Standard distance 600km
disposal	disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	CH	0	kg	3.44E-2	-	1	1.24	(3,1,1,1,3,3); company information, amount of deposited waste, own estimation for type
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	8.68E-1	4.00E-2	1	1.07	(1,1,1,1,1,3); Calculation for plastic parts burned after recycling
	treatment, glass production effluent, to wastewater treatment, class 2	CH	0	m3	2.63E-3	-	1	1.07	(1,1,1,1,1,3); company information
emission air	Heat, waste	-	-	MJ	4.41E+2	-	1	1.07	(1,1,1,1,1,3); Calculation
	Cadmium	-	-	kg	2.10E-8	-	1	5.09	(3,4,3,3,1,5); Rough estimation
	module materials			kg	16.0	17.6			including losses
	disposal			kg	0.9	0.0			

Tab. 9.7 EcoSpold meta information of CIS photovoltaic laminates and modules

ReferenceFunction	Name	photovoltaic laminate, CIS, at plant	photovoltaic panel, CIS, at plant
Geography	Location	DE	DE
ReferenceFuncti	InfrastructureProcess	1	1
ReferenceFuncti	Unit	m2	m2
	IncludedProcesses	Electricity use, materials, transport of materials, treatment of production wastes. Disposal after end of life. Process emissions not known (except Cd).	Electricity use, materials, transport of materials, treatment of production wastes. Disposal after end of life. Process emissions not known (except Cd).
	LocalName	Solarlaminat, CIS, ab Werk	Solarpaneel, CIS, ab Werk
	Synonyms	copper indium selenide//thin film//CIGS	Solarmodul//PV-module//copper indium selenide//thin film//CIGS
	GeneralComment	Production of photovoltaic thin film laminates by thermal vaporization in vacuum. The modules produced at Würth Solar have a size of 1.2m by 0.6m. The weight is 12.6kg. The efficiency is 10%. The rated nominal power is about 75-80Wp per module.	Production of photovoltaic thin film modules by thermal vaporization in vacuum. The modules produced at Würth Solar have a size of 1.2m by 0.6m. The weight is 12.6kg. The efficiency is 10%. The rated nominal power is about 75-80Wp per module.
	Category	photovoltaic	photovoltaic
	SubCategory	production of components	production of components
	Formula		
	StatisticalClassification		
	CASNumber		
TimePeriod	StartDate	1998	1998
	EndDate	2007	2007
	OtherPeriodText	Data refer to 2007. Production in 2006 was ramped up.	Data refer to 2007. Production in 2006 was ramped up.
Geography	Text	Data for Würth Solar in Germany.	Data for Würth Solar in Germany.
Technology	Text	Production technology of thin film CIS cells with thermal vaporization in vacuum.	Production technology of thin film CIS cells with thermal vaporization in vacuum.
Representativeness	Percent	50	50
	ProductionVolume	14.8 MW planned for 2007	14.8 MW planned for 2007
	SamplingProcedure	Literature data based on producer information.	Literature data based on producer information.
	Extrapolations	Data for coating materials derived from own assumptions.	none

9.4 Amorphous silicon (a-Si)

9.4.1 Introduction

The data availability with regard to amorphous silicon PV is very limited. Tab. 9.8 shows a summary of LCA results for the energy use for manufacturing a-Si panels in different studies, which are not relevant for the present study. The older studies rely on data published in 1994.[32] The study of Lewis & Keoleian (1997) only provides the sum of material and processing uses. An inventory based on this publication can be found in (Briem et al. 2004). The differences for the total energy use between different studies are small, while details might vary considerably. The most detailed inventory has been published for production of United Solar in the United States (Pacca et al. 2006).

Results for a-Si modules are published by the SENSE project (Shibasaki 2006). It is unclear whether or not the background and assumptions for these results will be published. The data have been investigated for Free Energy Europe.

The unit process raw data for this process are investigated for the production process at United Solar in the United States and are based on the available information.

Tab. 9.8 Cumulative energy use for the production of a-Si PV panels investigated in different studies (MJ-eq/m^2 panel). Further details can be found in the cited publications

Process stage	**Estimation for Europe**	**USA**	**USA**	**Japan 10MW**	**Japan 30MW**	**Japan 100MW**
cell material	50	871	834-861	n.d.	n.d.	n.d.
substrate and encapsulation	350	n.d.	n.d.	n.d.	n.d.	n.d.
cell production	400	491	n.d.	958	1078	746
overhead	250	0	n.d.	76	60	22
balance of system	150	0	ca. 119	609	449	410
Total for the laminate	**1200**	**491**	**ca. 969**	**1643**	**1587**	**1178**
Source	(Alsema 2000a)	(Lewis & Keoleian 1997)	(Pacca et al. 2006	(Kato et al. 1997b)	(Kato et al. 1997b)	(Kato et al. 1997b)

9.4.2 Product

Amorphous silicon (a-Si) alloy thin film technology offers an interesting opportunity to reduce materials cost of the solar cells. Because a-Si alloy absorbs light more efficiently than its crystalline counterpart, the a-Si solar cell thickness can be 100 times less than that of conventional cells. By utilizing a flexible, stainless steel substrate and polymer-based encapsulates, PV products utilizing this technology can be lightweight, flexible and durable.

9.4.3 Production process

The production process can be distinguished between single vs. multiple junction technologies. These have different thickness and different efficiencies. In particular, efficiency for triple junction is higher than for single junction. Besides, triple junction may work better with covered sky.

[32] Personal communication by Erik Alsema, 9.10.2006. "Unfortunately there are almost no inventory data on a-Si production. The major source is Paolo Frankl's Eclipse project, but for a-Si they used my own estimates from 1994 and let those check by one small producer (Free Energy Europe). A problem is also that there are only a few small producers in Europe, 1 or 2 in the USA. Most is produced in Japan. So it is difficult to organize an average data set, like I did in Crystal-Clear project"

Here we describe the process used by United Solar in the United States.[33] The cell is deposited using a vapour-deposition process at low temperatures.

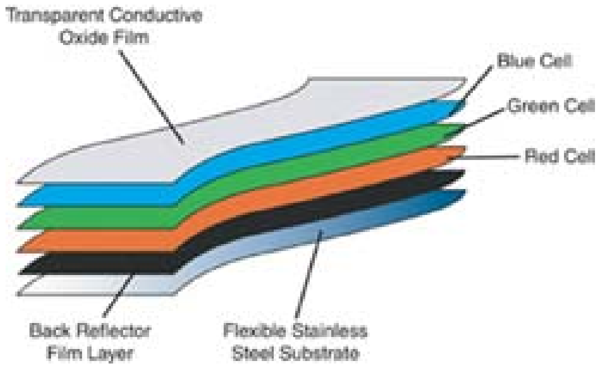


Fig. 9.4 Structure of United Solar's triple junction thin film cell

Amorphous materials with different light absorption properties can be deposited continuously, one on top of another, to capture the broad solar spectrum more effectively. This increases the energy conversion efficiency of the multi-cell device and improves the performance stability. The multi-junction approach of United Solar, as shown in Fig. 9.4, has resulted in higher efficiencies for the a-Si technology than for single junction cells.

For the manufacturing of PV modules a continuous roll-to-roll solar cell deposition process is used. In the manufacturing plant in Auburn Hills, Michigan, solar cells are deposited on rolls of stainless steel that are a mile-and-a half long using automated manufacturing machines. The a-Si alloy processor deposits the nine thin-film layers of the triple-junction cell on six rolls of stainless steel at a time.

The rolls of solar cell material can be processed further for use in a variety of photovoltaic products for different applications ranging from battery charging to large-scale grid-connected systems. Fig. 9.5 shows the manufacturing process for an a-Si module.

[33] Descriptions found on www.uni-solar.com.

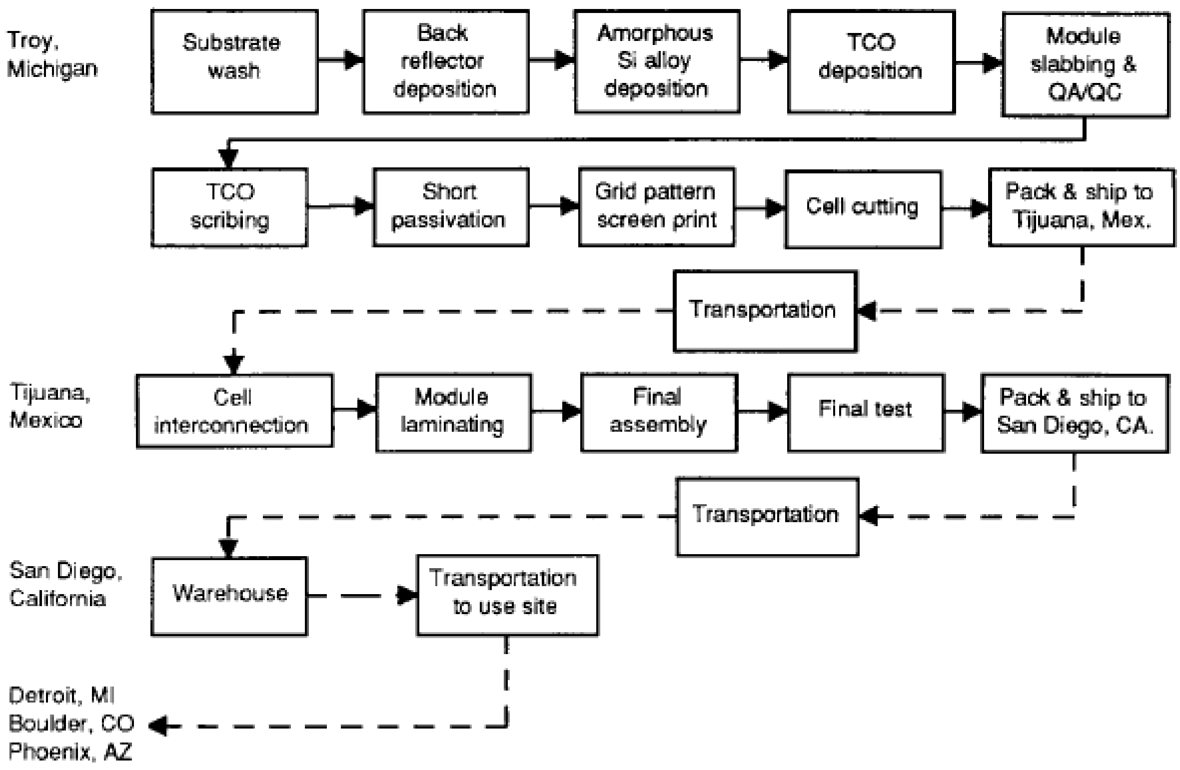


Fig. 9.5 **UPM-880 manufacturing process steps of tandem junction module. Solid lines denote in-plant material movement; dashed lines denote movement between plants (Keoleian & Lewis 1997)**

9.4.4 Life cycle inventories of a-Si laminates and panels

The unit process raw data of a-Si triple junction laminates and panels are shown in Tab. 9.9. Most of the data including data for transports are directly taken from the recent publication (Pacca et al. 2006). The amount of aluminium and steel necessary for the production of panels has been roughly estimated by (Pacca et al. 2006) with an older less detailed publication (Keoleian & Lewis 1997). It is assumed that silicon tetrahydride (SiH4) is purchased from a chemical factory.

Standard assumptions for the disposal of this infrastructure item after its lifetime have been used. It is assumed that the major metal materials and plastics can be recycled while smaller plastic parts will be incinerated. The amount of production wastes is assumed with the same amount as used for crystalline panels (GSS 2001), because specific data for production wastes were not available.

The laminates ASR128 produced at United Solar have a size of 2.3 m^2. The weight of used materials is 2.7 kg per m^2. The rated nominal power is about 128 Wp per laminate. The efficiency is estimated here for newer products with 6.45% (Tab. 11.2). A decreasing efficiency over the lifetime has no effect on the life cycle assessments as long as average kWh per kW_p figures can be used to calculate the electricity production.

Tab. 9.9 Unit process raw data for a-Si laminates and modules. Literature data

	3702	3703	##	3706	3707	3707	#	3709	3792	*Pacca 2006*	*Keoleian 1997*	*Briem 2004*
	Name	Location	InfrastructureProcess	Unit	photovoltaic laminate, a-Si, at plant	photovoltaic panel, a-Si, at plant	Uncertainty	StandardDeviation95%	GeneralComment	ASR128	UPM 880	a-Si Module
	Location				US	US				US	US	US
	InfrastructureProcess				1	1				0	0	0
	Unit				m2	m2				m2	m2	m2
product	photovoltaic laminate, a-Si, at plant	US	1	m2	1.00E+0	0				1.00	1.00	-
	photovoltaic panel, a-Si, at plant	US	1	m2	0	1.00E+0				-	-	1.00
technosphere	electricity, medium voltage, at grid	US	0	kWh	4.82E+1	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	4.82E+1	-	4.37E+1
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	5.89E+0	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	5.89E+0	-	
infrastructure	photovoltaic panel factory	GLO	1	unit	4.00E-6	-	1	3.02	(1,4,1,3,1,3); Assumption	-	-	
water	tap water, at user	RER	0	kg	3.97E+1	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	3.97E+1	-	
manufacturing	wire drawing, copper	RER	0	kg	6.68E-2	-	1	1.22	(4,3,2,1,1,na); Assumption	6.68E-2	-	
	sheet rolling, steel	RER	0	kg	9.64E-1	2.18E+0	1	1.22	(4,3,2,1,1,na); Assumption	9.64E-1	2.18E+0	
materials	photovoltaic laminate, a-Si, at plant	US	1	m2	-	1.00E+0	1	1.22	(4,3,2,1,1,na); Assumption	-	-	
	aluminium alloy, AlMg3, at plant	RER	0	kg	1.43E-2	3.34E+0	1	1.13	(3,3,2,1,1,na); Pacca 2006	1.43E-2	3.34E+0	3.34E+0
	copper, at regional storage	RER	0	kg	6.68E-2	-	1	1.13	(3,3,2,1,1,na); Busbar and wire	6.68E-2	-	
	steel, low-alloyed, at plant	RER	0	kg	9.64E-1	2.18E+0	1	1.13	(3,3,2,1,1,na); Pacca 2006	9.64E-1	3.18E+0	3.18E+0
	brazing solder, cadmium free, at plant	RER	0	kg	2.62E-3	-	1	1.13	(3,3,2,1,1,na); Solder lead	2.62E-3	-	
	soft solder, Sn97Cu3, at plant	RER	0	kg	9.71E-3	-	1	1.13	(3,3,2,1,1,na); Solder tin	9.71E-3	-	
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.10E+0	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	1.10E+0	-	
	packaging film, LDPE, at plant	RER	0	kg	3.10E-1	-	1	1.13	(3,3,2,1,1,na); Madico, window film	3.10E-1	-	
	polyvinylfluoride film, at plant	US	0	kg	1.23E-1	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	1.23E-1	2.22E+0	2.22E+0
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	3.58E-2	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	3.58E-2	-	
	synthetic rubber, at plant	RER	0	kg	6.76E-2	-	1	1.13	(3,3,2,1,1,na); Duraseal, coating of cables and rubber wire insulation	6.76E-2	-	
coating	silicon tetrahydride, at plant	RER	0	kg	3.58E-3	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	3.58E-3	-	
	indium, at regional storage	RER	0	kg	8.94E-4	-	1	1.26	(3,4,2,1,3,na); Indium tin oxide, amount less than 0.05%	8.94E-4	-	
	cadmium telluride, semiconductor-grade, at plant	US	0	kg	8.94E-4	-	1	1.26	(3,4,2,1,3,na); Cadmium stannate (Cd2SnO4), amount less than 0.05%	8.94E-4	-	
	phosphoric acid, fertiliser grade, 70% in H2O, at plant	US	0	kg	7.50E-5	-	1	1.13	(3,3,2,1,1,na); Phosphine (H3P)	7.50E-5	-	
auxiliaries	oxygen, liquid, at plant	RER	0	kg	4.85E-4	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	4.85E-4	-	
	hydrogen, liquid, at plant	RER	0	kg	2.18E-2	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	2.18E-2	-	
packaging	polyethylene, LDPE, granulate, at plant	RER	0	kg	1.84E-2	-	1	1.13	(3,3,2,1,1,na); Pacca 2006	1.84E-2	-	
transport	transport, lorry >16t, fleet average	RER	0	tkm	8.49E-3	-	1	2.09	(4,5,na,na,na,na); Standard distance 15km disposal	-	-	
	transport, transoceanic freight ship	OCE	0	tkm	9.07E+0	6.98E+0	1	2.02	(3,3,2,1,1,na); Pacca 2006, specific investigation of supplies	9.07E+0	-	
	transport, freight, rail	RER	0	tkm	1.50E+0	4.16E+0	1	2.02	(3,3,2,1,1,na); Pacca 2006, specific investigation of supplies	1.50E+0	-	
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	3.00E-2	-	1	1.13	(1,4,1,3,1,3); Alsema (personal communication) 2007, production waste	-	-	
	disposal, rubber, unspecified, 0% water, to municipal incineration	CH	0	kg	6.76E-2	-	1	1.22	(4,3,2,1,1,na); Calculation for end of life disposal	-	-	
	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	1.23E-1	-	1	1.22	(4,3,2,1,1,na); Calculation for end of life disposal	-	-	
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	3.46E-1	-	1	1.22	(4,3,2,1,1,na); Calculation for end of life disposal	-	-	
	treatment, glass production effluent, to wastewater treatment, class 2	CH	0	m3	3.97E-2	-	1	1.22	(4,3,2,1,1,na); Calculation with water use	-	-	
emission air	Heat, waste	-	-	MJ	1.74E+2	-	1	1.29	(3,4,3,3,1,5); Calculation	-	-	
information	total weight of used materials			kg	2.7	8.2				2.7	8.7	8.7
	disposal			kg	0.6	0.0				0.0	0.0	0.0
	Capacity			Wp	64.5	64.5				56.5	53.7	53.7
	Efficiency			%	6.5%	6.5%				5.6%	5.4%	5.4%

Tab. 9.10 EcoSpold meta information of a-Si photovoltaic laminates and modules

ReferenceFunction	Name	photovoltaic laminate, a-Si, at plant	photovoltaic panel, a-Si, at plant
Geography	Location	US	US
ReferenceFuncti	InfrastructureProcess	1	1
ReferenceFuncti	Unit	m2	m2
	IncludedProcesses	Electricity and heat use, materials, transport of materials, disposal of wastes and the product. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the lamination process.	Electricity and heat use, materials, transport of materials, disposal of wastes and the product. Data for direct air and water emissions were not available. It can be expected that small amount of NMVOC will be emitted from the lamination process.
	LocalName	Solarlaminat, a-Si, ab Werk	Solarpaneel, a-Si, ab Werk
	Synonyms	Solarmodul//PV-module//amorphous silicon	Solarmodul//PV-module//amorphous silicon
	GeneralComment	Production of photovoltaic thin film laminates. Deposition of nine thin-film layers on the triple-junction cell. The laminates ASR128 produced at United Solar have a size of 2.3 m2. The weight is 2.7 kg per m2. The rated nominal power is about 128Wp per laminate. The efficiency is estimated here for newer products with 6.45% at the beginning of the life time. Degradation has to be taken into account with achieved yields.	Production of photovoltaic thin film modules. Deposition of nine thin-film layers on the triple-junction cell. The modules produced at United Solar have a size of 2.3 m2. The weight is 8.2 kg per m2. The efficiency is 6.45% at the beginning of the life time. Degradation has to be taken into account with achieved yields. The rated nominal power is about 128Wp per module.
	Category	photovoltaic	photovoltaic
	SubCategory	production of components	production of components
	Formula		
	StatisticalClassification		
	CASNumber		
TimePeriod	StartDate	1997	1997
	EndDate	2005	2005
	OtherPeriodText	Data refer to 2005. Some are extrapolated from older information.	Data refer to 2005. Some are extrapolated from older information.
Geography	Text	Data for United Solar in the United States.	Data for United Solar in the United States.
Technology	Text	Production technology of thin film a-Si cells. The modules contain triple junction cells, which are made in a continuous roll-to-roll deposition on stainless steel. The cell is deposited using a vapour-deposition process at low temperatures.	Production technology of thin film a-Si cells. The modules contain triple junction cells, which are made in a continuous roll-to-roll deposition on stainless steel. The cell is deposited using a vapour-deposition process at low temperatures.
Representativen	Percent	100	100
	ProductionVolume	8.1 MW in 2005	8.1 MW in 2005
	SamplingProcedure	Literature data based on producer information.	Literature data based on producer information.
	Extrapolations	Data for disposal derived from own assumptions.	Packaging estimated with data for crystalline modules.

10 Balance of System (BOS)

10.1 Overview for mounting systems

Panels are mounted on top of houses and laminates are integrated into slanted roofs and façades. Flat roof systems are mounted on the roof. Process data include construction materials (e.g. aluminium, plastics, steel, etc.) and process energy. Transports of the photovoltaic system from the manufacturing site to the place of operation include personnel transports for mounting.

The description for different mounting systems in this chapter covers photovoltaic plants with a capacity of 3 kW_p. The unit process raw data are recorded per m^2 of total panel or laminate surface.

For each type of mounting system we describe only one possible example. A recent market survey for mounting systems has been published by Siemer (2003; 2006; 2007; 2008). In this survey the total weight of several dozen of different mounting systems is reported without providing more detailed information on the type of materials used. In order to achieve an average weight for each type of mounting system, the weights of the different mounting system models were weighted by their installed capacity in Europe. Recent information from literature (de Wild-Scholten & Alsema 2007) and producers has been used to estimate the unit process raw data for the weight of used materials. Data from manufacturers were available for the following products (Tab. 10.1).

For economic and energetic reasons some of the producers do not use aluminium any more in their mounting system. Other materials, e.g. plastics or wood are used instead (Völlmecke 2000). The trend towards larger panels should decrease the specific material consumption.

Tab. 10.1 Products investigated in view of the update of the unit process raw data

Type	Product	Company
flat roof	AluStand	www.solarmarkt.com
flat roof	Brühler	www.buehler-energy.ch [34]
flat roof	Schletter	www.solar.schletter.de [35]
façade	Brühler	www.buehler-energy.ch
slanted roof, integrated	SOLRIF	www.solrif.ch
slanted roof, integrated	Schletter	(de Wild-Scholten & Alsema 2007), [36]
slanted roof, mounted	AluStand	www.solarmarkt.com , www.alustand.ch
slanted roof, mounted	Brühler	www.buehler-energy.ch
slanted roof, mounted	TectoSun	www.SonnenStromAG.de
slanted roof, mounted	Schletter	(de Wild-Scholten & Alsema 2007)

An earlier data collection was based on telephone calls and two student theses at the ETH Zurich (Schwarz & Keller 1992) and <Degen et al. 1991>. These reports describe the ecological and energetic pay back time of photovoltaics (3 kW_p and 9 kW_p, respectively). The different types of mounting systems were described in a handbook for tilers <Prinz et al. 1992>. The examples for slanted roof and façade plants have been investigated for singlecrystalline cells. The flat roof example was investigated for multicrystalline cells. The average consumption of packaging material for the finished PV plants is calculated with a correction factor from this old information, which accounts for the average weight of today installations. The correction factor is discussed in chapter 11.3.

[34] Personal communication with Urs Bühler, Energy Systems and Engineering, 24.1.2007

[35] Personal communication with C. Heller, Schletter Solar-Montagetechnik, CH, 17.1.2007

[36] Personal communication with C. Heller, Schletter Solar-Montagetechnik, CH, 17.1.2007

10.2 Slanted roof, mounted

10.2.1 Overview

This is a common and simple type of mounting system. It is necessary to have a faultless roof. The mounting system uses wood, aluminium or steel that is directly attached to the rafter of the roof. Good ventilation is ensured with a distance of about 10 cm from the roof surface. Thus efficiency losses due to higher temperatures are minimised.

The estimation is mainly based on (Schwarz & Keller 1992). The original data have been adapted based on information in <Prinz et al. 1992> and <Sutter 1993>. Own assumptions are used for missing items such as treatment of wastes.

10.2.2 Construction process

The tiler mounts the panels on the roof. The roof surface might be temporally removed at certain parts in order to directly fix the mounting system on the rafter (Fig. 10.1). The solar panels are fixed to this system.

Fig. 10.1 Mounting of solar panels on a slanted roof. The figure shows the view on a mounting in the roof construction, www.conergy-systems.de

10.2.3 Material use

Data for the material use were available from different producers (Tab. 10.2). Data for 2006 are reported by de Wild-Scholten & Alsema (2007). These figures are lower because a large module and a light version of mounting structure have been chosen.[37] The amount of aluminium used for the system is estimated based on recent information from producers and the actual average weight of such systems according to Siemer (2008) with 2.8 kg/m^2. The amount of steel is estimated with 1.5 kg/m^2.[38]

Tab. 10.2 Data of the material use of a mounted slanted roof system for one m^2

	this study 2008 kg/m2	TectoSun 2007 kg/m2	TectoSun 2006 kg/m2	Brühler 2007 kg/m2	Schletter 2007 kg/m2	Schletter 2006 kg/m2	AluStand 2007 kg/m2	Briem 2004 kg/m2
aluminium	**2.8**	1.6	0.54	2.1	1.9	0.97	3.0	2.7
steel	**1.5**	1.6	0.49	1.1	0.7	0.7	1.0	1.2
rest	**0.1**	-	-	-	-	-	-	-
total weight	**4.5**	3.2	1.0	3.2	2.6	1.7	4.0	3.9

The use of packaging materials is shown in Tab. 10.3 according to a now outdated study. Packaging materials are mainly used for small parts. For the use of packages a correction factor of 1.54 based on Siemer (2008) is used to calculate the amount with the older data shown in Tab. 10.3 and the actual average weight of such systems. For the calculation of the conversion factor consider chapter 10.8.

Tab. 10.3 Old data of the material use of a mounted slanted roof system for a 3 kWp-plant with 22 m^2 (Schwarz & Keller 1992) which are used for the estimation on packaging

	Mass kg	Source	Considered with correction factor
Packaging			
Cardboard	1.9	(Schwarz & Keller 1992)	x
Polystyrene XPS	0.1	(Schwarz & Keller 1992)	x
Plastics (sticky tape, rope)	0.02	(Schwarz & Keller 1992)	x
Total	**2.02**		

10.2.4 Energy use for mounting

Most of the energy use for mounting is due to the electricity used for drilling and screwing (Tab. 10.4). The data have been investigated by Schwarz (1992, annexe p. 14). Additionally the use of a lift for materials is taken into account. The electricity use seems to be quite small, but could not be verified for the present study. The electricity use for erection of the mounting system is not allocated to the mounting system dataset but to the 3kW$_p$ PV plant datasets (see chapter 11.6).

[37] A profile for a large module has a smaller amount of Al per m^2 than for a small module. Here a module size of 6 x 10 cells of 156 mm x 156 mm has been used (personal communication M. de Wild, 6.2007).

[38] Data provided in personal communication for the products TectoSun, AluStand and (de Wild-Scholten & Alsema 2007)

Tab. 10.4 Energy use for mounting of a 3 kWp-slanted roof plant

energy for mounting	electricity	Source
	kWh	
screws	0.1	
steel bracket mounting	0.07	(Schwarz & Keller 1992)
aluminium-U-Profile mounting	0.02	(Schwarz & Keller 1992)
Material lift	0.04	<Wiest 1993>
Total energy for mounting	**0.23**	

10.2.5 Disassembly and disposal

It is assumed that all recyclable parts of the mounting system will be reused. Thus processes for the disposal of building materials are taken into account. The wood is incinerated in a municipal waste incineration plant.

10.3 Slanted roof, integrated

10.3.1 Overview

The search for material efficient and aesthetic mounting of solar laminates has lead to the idea of integrating the laminates directly in the roof construction instead of mounting them above it. Thus, the PV-plants do not only produce electricity, but also replace roof tiles. This allows to use frameless laminates instead of framed panels, which further reduces the amount of necessary materials.

There are different possibilities for the assembly. Besides using laminates, there is also a possibility of using solar tiles. Here we investigate a system produced by the company Schweizer AG, CH-Hedingen.

The data have been investigated by <Prinz et al. 1992> and <Wiest 1993>. Data for smaller items (e.g. screws, energy for mounting) are based on older literature (Schwarz & Keller 1992) and are modified with own assumptions.

10.3.2 Construction process

The roof tiles are removed in the area foreseen for the solar laminates. Then steel profiles are screwed to the tile slats (Fig. 10.2). Different aluminium profiles are used to make a frame for the laminate. A rubber is attached to these profiles. The laminates are placed within these frames and connected to the electric system. All edges are closed with rubber or silicones. Steel sheets are mounted at the gap between roof tiles and solar laminates.

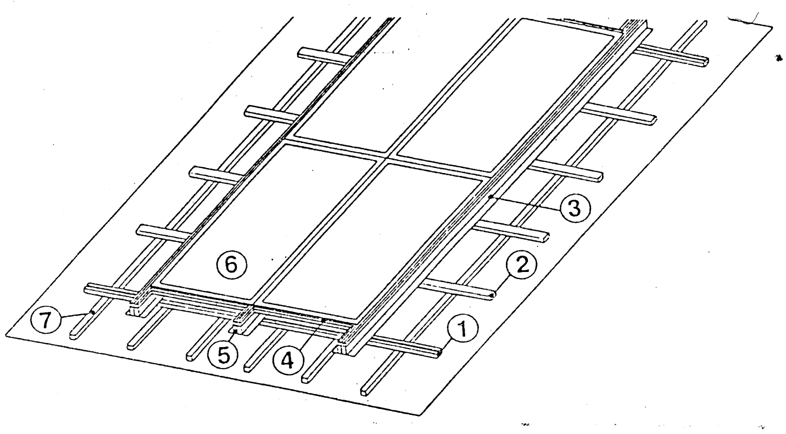


Fig. 10.2 Old example for a construction for the integrated mounting on a slanted roof Legend: 1. C-Profile (steel) 2. tiles slats (Wood) 3. side profile (aluminium) 4. cross section (aluminium) 5. Longitudinal profile (aluminium) 6. PV-Laminate. Source: <Prinz et al. 1992>

10.3.3 Material use

Data for the actual material use were available from some producers (Tab. 10.5). Data for 2006 are reported by de Wild-Scholten & Alsema (2007).The amount of aluminium is estimated based on recent information from producers and the actual average weight of the installation according to Siemer (2008) with 2.2 kg/m^2. The amount of steel is estimated with 0.2 kg/m^2.[39]

The possible allocation between the two functions of providing a mounting system and replacing the normal roof tiles has been discussed in a previous version of this life cycle inventory (Frischknecht et al. 1996). It was concluded that only a minor part of the total expenses should be allocated to the replacement of normal building materials. This share is neglected here.

Tab. 10.5 List of materials for the mounting structure integrated in a slanted roof with one m^2 panels

	this study 2008 kg/m2	SOLRIF 2007 kg/m2	SOLRIF 2006 kg/m2	Schletter 2006 kg/m2
aluminium	**2.2**	2.2	1.7	1.2
HDPE	**0.028**	0.032	0.032	-
polyurethane	**0.018**	0.042	-	-
rubber	**1.2**	-	1.4	1.4
steel	**0.200**	0.094	0.080	0.280
total weight	**3.7**	2.3	3.2	2.9

For all packages a correction factor of 1.32 is used to calculate the amount with the data shown in

39 Data provided in personal communication for the products SOLRIF and (de Wild-Scholten & Alsema 2007)

Tab. 10.6, based on Schwarz et al. (1992, annexe p. 20) and the actual average weight of the installation according to Siemer (2008).

Tab. 10.6 List of packaging materials for 3 kWp-plant integrated in a slanted roof with 22 m^2 panels

		Mass	Source
		kg	
Packaging	Cardboard	1.9	(Schwarz & Keller 1992)
	Polystyrene XPS	0.1	(Schwarz & Keller 1992)
	Total	2	

10.3.4 Energy use for mounting

The mounting structure is similar to the mounted slanted roof structure. Therefore, the same figures for the energy use as shown in Tab. 10.4 are applied here.

10.3.5 Disassembly and disposal

The disassembly of the mounting structure is taken into account. All larger parts will be recycled. Smaller parts (listed in Tab. 10.6) are disposed of.

10.4 Flat roof

10.4.1 Overview

The main challenge for the installation of flat roof plants is the bracing to the roof. Any damage due to weather conditions, e.g. wind, should be avoided, but on the other side the roof itself should not be damaged e.g. due to the weight of the system or screws.

10.4.2 Construction process

The different parts of the mounting system are delivered to the construction site. Most of the mass is the gravel for the foundation. The gravel would also be necessary for flat roof without a PV plant. Insulating mats, aluminium profiles and smaller parts are the main parts of the mounting system. First the flat roof is cleaned from sand and gravel. A mat made from recycled plastic is attached for the protection of the roof. Than a foundation is made and fixed with loose gravel placed on this plastic sheet. Aluminium profiles are mounted and the panels are fixed to this foundation.

10.4.3 Material use

Data for mounting systems on flat roofs were available from some producers (Tab. 10.7). The amount of aluminium is estimated based on recent information from producers and the average weight according to Siemer (2008) with 2.5 kg/m^2. Recycled polyethylene mats (SOLREC) are used to fix the mounting structure. The amount of Solrec recycling plastic is estimated with 1.9 kg polyethylene HDPE/m^2.[40] Gravel is used as a weight on the Solrec plastics. An amount of 115 kg/m^2 is necessary, but not considered here because it would be used also on a normal flat roof.

[40] Data provided in personal communication for the products AluStand

Tab. 10.7 List of materials used for mounting systems on flat roof per m² of panels

	this study 2008 kg/m2	AluStand 2007 kg/m2	Brühler 2007 kg/m2	Schletter 2007 kg/m2
aluminium	**2.5**	5.0	5.9	7.8
HDPE	**1.9**	8.0	6.3	-
steel	**0.3**	-	0.1	1.9
total weight	**4.7**	13.0	12.3	9.7

Packaging materials are estimated based on literature (Schwarz & Keller 1992) (Tab. 10.8) are applied and corrected with a factor of 0.40 to consider the actual average weight according to Siemer (2008).

Tab. 10.8 List of packaging materials for mounting of a universal heavy duty bracing for 24.3 m² of panels

	Mass kg	Source
Packaging	0	
Cardboard	1.1	(Schwarz & Keller 1992)
Polystyrene XPS	0.1	(Schwarz & Keller 1992)
Total	1.2	

10.4.4 Energy use for mounting

The energy use for mounting has been investigated by Schwarz et al. (1992, annexe p. 14) (Tab. 10.9). All parts have to be lifted to the roof with a crane. For single family houses this can be done with the crane attached to a truck. For higher buildings an extra crane must be used. The necessary transport of this crane is considered. Distances have been increased a little bit compared to the ones reported in order to account for the operation of the crane (2∗40 km). The electricity use for erection of the mounting system is not allocated to the mounting system dataset but to the 3kW$_p$ PV plant datasets (see chapter 11.6).

Tab. 10.9 Energy use for mounting universal heavy duty bracing (Schwarz & Keller 1992)

energy for mounting	Electricity
	kWh
steel consoles mounting	0.02
drilling	1.0

10.4.5 Disassembly and disposal

As for other systems we assume a disassembly and recycling for the larger metal parts of the mounting structure.

10.5 Façade, mounted

10.5.1 Overview

The mounting of PV-panels to façades is mainly used for industrial buildings. There are different mounting structures.

10.5.2 Construction process

Five panels are fixed together on an aluminium profile. This is attached to the façade. If available the modules are fixed to the construction steel in the wall.

10.5.3 Material use

The use of materials according to older studies is shown in Tab. 10.10. New data from one company can be found in Tab. 10.11.

A correction factor of 0.81 is used to calculate the amount with the data shown in the table and the actual average weight according to Siemer (2008).

Tab. 10.10 List of materials for the mounting structure of a 3 kWp-plant mounted on a façade with 22 m²

		Mass	Source
		kg	
fixing Module	armature barn steel	38	<Brunschweiler 1993>
	aluminium - profile	72	<Brunschweiler 1993>
	steel plate	3	(Schwarz & Keller 1992)
	mounting system steel	8.1	(Schwarz & Keller 1992)
packaging	cardboard	1.1	(Schwarz & Keller 1992)
	polystyrene XPS	0.05	(Schwarz & Keller 1992)
	plastics (sticky tape, rope)	0.01	(Schwarz & Keller 1992)
	Total	122.26	

Tab. 10.11 List of materials for the mounting structure of a 3 kWp-plant mounted on a façade per m²

	this study	Bühler
	kg/m2	kg/m2
aluminium	2.6	2.9
steel	1.8	1.1
total weight	4.4	4.0

10.5.4 Energy use for mounting

The energy for mounting is mainly used by a screwdriver. Literature data have been used for the assessment (Schwarz & Keller 1992). The electricity use for erection of the mounting system is not allocated to the mounting system dataset but to the $3kW_p$ PV plant datasets (see chapter 11.6).

Tab. 10.12 Energy use for construction of the mounting structure at a façade

energy for mounting	electricity kWh/m^2	Source
screws	0.02	(Schwarz & Keller 1992)
aluminium profile mounting	0.02	(Schwarz & Keller 1992)

10.5.5 Disassembly and disposal

It is assumed that the plant will be disassembled after use. Larger parts are recycled and smaller parts (listed in Tab. 10.10) are incinerated.

10.6 Façade, integrated

10.6.1 Overview

The integration of solar laminates in a façade is mainly useful for new buildings or as a part of renovation activities. It is more frequently used for industrial buildings. Conventional façade elements can be replaced by solar panels. Thus, quite a range of different possibilities exists for the mounting structure. The following data are based on literature <RusterWood 1993>, <Prinz et al. 1992> and <Degen et al. 1991> and own assumptions.

10.6.2 Construction process

The assembly process is dependent on the type of façade. Here we assume a commonly used construction with aluminium profiles („Aluhit“).

10.6.3 Material use

About 75 kg of aluminium are used for the basic construction structure for 22m^2 of panels <Gabriel 1993>. A correction factor of 0.96 calculated with the actual average weight according to Siemer (2008) is used to calculate the amount. The surplus material use compared to a conventional façade is mainly due to the use of laminates with less own stability than panels. As already discussed for the PV-plant integrated in a slanted roof it must be discussed which part of the necessary mounting structure should be allocated to the PV-plant and which part should be allocated to the normal construction process of the façade.

An earlier assessment showed that a part of the necessary mounting structure should be allocated to the function of the building (Frischknecht et al. 1996). Here we allocated the full structure to the PV-plant. It is recommended to make a sensitivity analysis in detailed case studies. Therefore it is suggested that 70% to 100% of the mounting structure should be allocated to the PV-plant and 30% to 0% to the construction of the façade.

10.6.4 Energy use for mounting

The figures shown in Tab. 10.12 represent the energy use for screwing and mounting of aluminium profiles.

10.6.5 Disassembly and disposal

It is assumed that the plant will be disassembled after use. Larger parts of the support structure are recycled and smaller parts are incinerated.

10.7 Open ground

Life cycle inventory data describing an installation on open ground are not yet elaborated. Material weights are provided in de Wild-Scholten & Alsema (2007). The material use (excluding foundation) is about 12 kg/m^2 which is mainly steel.

10.8 Life cycle inventory of mounting systems

Tab. 10.13 shows the unit process raw data of mounting systems for solar panels and laminates. Tab. 10.24 shows the EcoSpold meta information of these systems. The data are investigated per m^2 of installed panel surface. It has to be noted that the amount of materials per m^2 is quite variable. It depends on factors like actual panel size and location of installation. Thus, for example in Switzerland the mounting structure must be stable also with a certain snow load on the panel while this might not be necessary in Southern Europe. Also the expected maximum wind velocities influence the amount of materials used in the mounting structure. Moreover, larger panels need less amount of mounting materials per square metre.

Siemer (2008) has investigated the actual weight for a range of different mounting system products. In Tab. 10.13 the maximum and minimum weight of today mounting systems products are calculated. The overview shows a large variation. Therefore, the weights of the different mounting system models were weighted by their installed capacity in Europe in order to achieve an average weight for each type of mounting system. Fig. 10.3 displays the weight and the installed capacity of the mounting system products available in 2007. Products with high installed capacity contribute substantially to the calculated average weight of the specific mounting system, whereas sparsly sold products do not contribute significantly. Some uncertainty exists because the type of used materials might differ considerably.

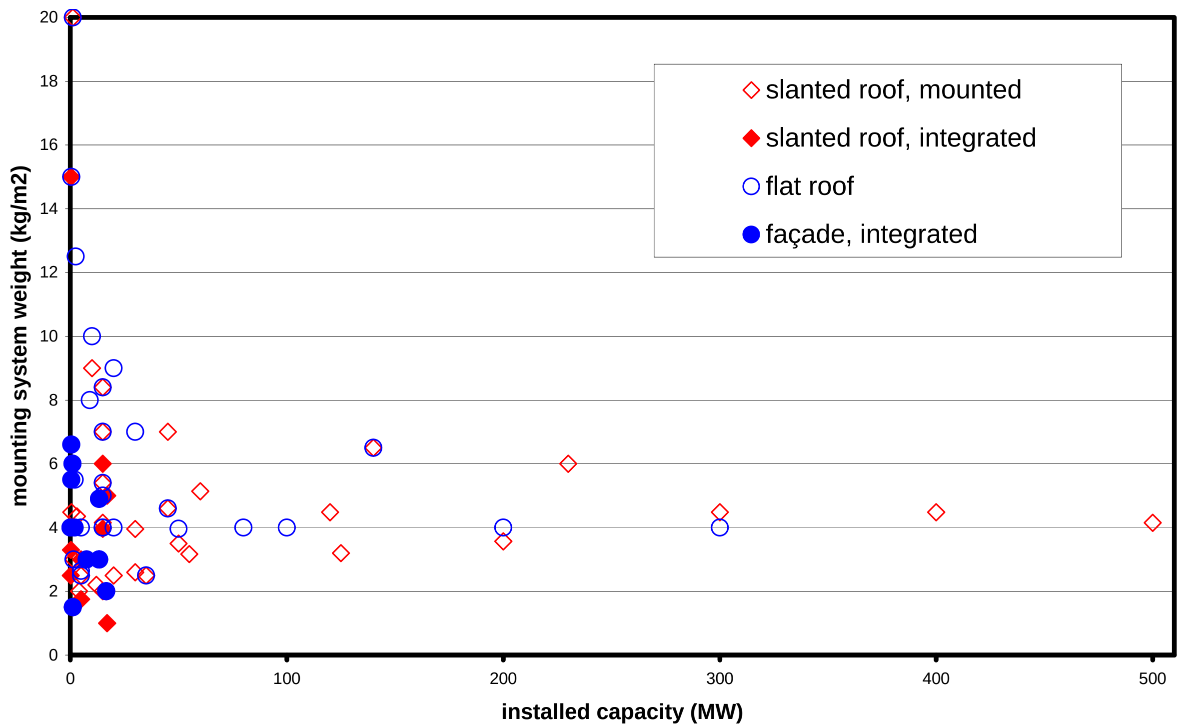


Fig. 10.3 Weight of mounting systems. Data source: Siemer 2008

The data quality for the construction process should be improved in future studies. Due to the improved production chains for the PV panels the mounting structure contributes more to the total environmental burden caused by photovoltaic electricity.

The comparison of actual mean weights and the weight of the investigated systems has been used for calculating a correction factor reported at the bottom of Tab. 10.13. The specific weight of mounting systems for façade systems has decreased slightly and for slanted-roof systems it decreased considerably compared to the data investigated in the early nineties. The correction factors are considered in the unit process raw data describing the mounting structure of 3 kW_p plants shown in Tab. 11.4 and Tab. 11.5.

The life cycle inventory of the production of mounting systems does not take into account process emissions such as dust, because information is not available. Standard distances for the transport of materials to the production plant are taken into account. The transport to the final mounting place and the energy use for the construction process is considered in the assembly of the photovoltaic power plant (see chapter 11) because it includes also the energy e.g. for lifting the laminates and panels.

The high variability concerning the material weight per m^2 has been considered with a basic uncertainty of 2 for all material inputs and waste treatment services.

Tab. 10.13 Unit process raw data of different mounting systems, range of plant weights investigated for the year 2000, correction factor used in this study

	Name	Location	Infrastructur	Unit	facade construction, mounted, at building	facade construction, integrated, at building	flat roof construction, on roof	slanted-roof construction, mounted, on roof	slanted-roof construction, integrated, on roof	Uncertainty	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1			
	Unit				m2	m2	m2	m2	m2			
technosphere	aluminium, production mix, wrought alloy, at plant	RER	0	kg	2.64E+0	3.27E+0	2.52E+0	2.84E+0	2.25E+0	1	2.05	(1,2,1,1,1,na); Literature and own estimations
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	4.03E-2	-	1.83E-2	1.33E-1	1.14E-1	1	2.18	(3,4,3,1,3,5); Schwarz et al. 1992
	polyethylene, HDPE, granulate, at plant	RER	0	kg	7.32E-4	-	1.92E+0	1.40E-3	2.82E-2	1	2.05	(1,2,1,1,1,na); Literature and own estimations, recycled PE
	polystyrene, high impact, HIPS, at plant	RER	0	kg	3.66E-3	-	8.30E-3	7.02E-3	6.02E-3	1	2.18	(3,4,3,1,3,5); Schwarz et al. 1992
	polyurethane, flexible foam, at plant	RER	0	kg	-	-	-	-	1.84E-2	1	2.05	(1,2,1,1,1,na); Literature and own estimations
	synthetic rubber, at plant	RER	0	kg	-	-	-	-	1.24E+0	1	2.05	(1,2,1,1,1,na); Literature and own estimations
	steel, low-alloyed, at plant	RER	0	kg	1.80E+0	-	2.67E-1	1.50E+0	2.00E-1	1	2.05	(1,2,1,1,1,na); Literature and own estimations
	gravel, unspecified, at mine	CH	0	kg	-	-	-	-	-	1	2.18	(3,4,3,1,3,5); not accounted
	section bar extrusion, aluminium	RER	0	kg	2.64E+0	3.27E+0	1.22E+0	3.03E+0	2.25E+0	1	2.18	(3,4,3,1,3,5); Estimation
	sheet rolling, steel	RER	0	kg	1.10E-1	-	2.67E-1	1.50E+0	-	1	2.18	(3,4,3,1,3,5); Estimation
	section bar rolling, steel	RER	0	kg	1.69E+0	-	-	-	2.00E-1	1	2.18	(3,4,3,1,3,5); Brunschweiler 1993
transport	transport, lorry >16t, fleet average	RER	0	tkm	2.24E-1	1.64E-1	2.56E-1	2.25E-1	2.07E-1	1	2.14	(4,5,na,na,na,na); Standard distance 50km
	transport, freight, rail	RER	0	tkm	1.61E+0	6.54E-1	1.05E+0	1.50E+0	8.52E-1	1	2.14	(4,5,na,na,na,na); Standard distances 200km, 600km
	transport, van <3.5t	RER	0	tkm	4.44E-1	3.27E-1	4.72E-1	4.34E-1	3.75E-1	1	2.18	(3,4,3,1,3,5); 100km to construction place
disposal	disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	0	kg	4.03E-2	-	1.83E-2	1.33E-1	1.14E-1	1	2.18	(3,4,3,1,3,5); Calculated with use
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	7.32E-4	-	1.92E+0	1.40E-3	1.29E+0	1	2.18	(3,4,3,1,3,5); Disposal of plastics parts at end of life
	disposal, building, polystyrene isolation, flame-retardant, to final disposal	CH	0	kg	3.66E-3	-	8.30E-3	7.02E-3	6.02E-3	1	2.18	(3,4,3,1,3,5); Disposal of plastics parts at end of life
product	facade construction, mounted, at building	RER	1	m2	1.00E+0	0	0	0	0			
	facade construction, integrated, at building	RER	1	m2	-	1.00E+0	0	0	0			
	flat roof construction, on roof	RER	1	m2	-	-	1.00E+0	0	0			
	slanted-roof construction, mounted, on roof	RER	1	m2	-	-	-	1.00E+0	0			
	slanted-roof construction, integrated, on roof	RER	1	m2	-	-	-	-	1.00E+0			
information	total weight, materials			kg	4.5	3.3	4.7	4.5	3.9			Sum from the inventory
	total weight, structure			kg	4.4	3.3	4.7	4.3	3.7			Sum from the inventory
	panel area			m2	1.0	1.0	1.0	1.0	1.0			
	minimum weight, construction			kg		1.5	1.5	1.0	1.0			Siemer 2008
	maximum, construction			kg		12.5	20.0	20.0	15.0			Siemer 2008
	number, examples			1		10	34	35	10			Siemer 2008
	mean, construction, 2008, weighted with the installed capacity			kg	**4.5**	**3.3**	**4.7**	**4.5**	**3.7**			Siemer 2008
	standard deviation			kg		1.2	3.1	1.2	2.0			Siemer 2008
	correction factor			%	0.81	0.96	0.40	1.54	1.32			Calculated for this study
	mean, construction, 2007, ecoinvent v2.0			kg	4.0	3.5	6.3	4.0	3.5			Siemer 2007
	mean, construction, 2003, ecoinvent v1.0			kg	4.9		6.2	4.4				Siemer 2003

10.9 Inverters

10.9.1 Introduction

The primary task of inverters is to transform the direct current (e.g. produced by solar cells) into alternating current with a frequency of 50 cycles per second in Europe. After a transformation to low-voltage-level (normally to 230V), the electric current can be feed into the grid.

Characterisation

An inverter consists in general of a few parts: transformers, electronic components as control units, a case and some connectors. This part has to fulfil the following tasks: Transform the electricity from direct current (DC) to alternate current (AC), transform into appropriate voltage (e.g. 230V), and additionally synchronize the voltage with the grid. The inverter fulfils also different electronic tasks like the maximum-power–point-tracking[41] as well as the automatic switch on/off. However, it is not the subject of this work to give a detailed description about inverters, further information is given in (Häberlin 1991) and other authors in the literature.

As a matter of principle, the mass of the inverter in general decreases with the nominal AC power (see Fig. 10.5). Between 2 and 200 kW the mass per kW depends on the inverter and ranges between 5 and 15 kg/kW. Above 400 kW the weight tends to be between 4 kg/kW and 7 kW/kg.

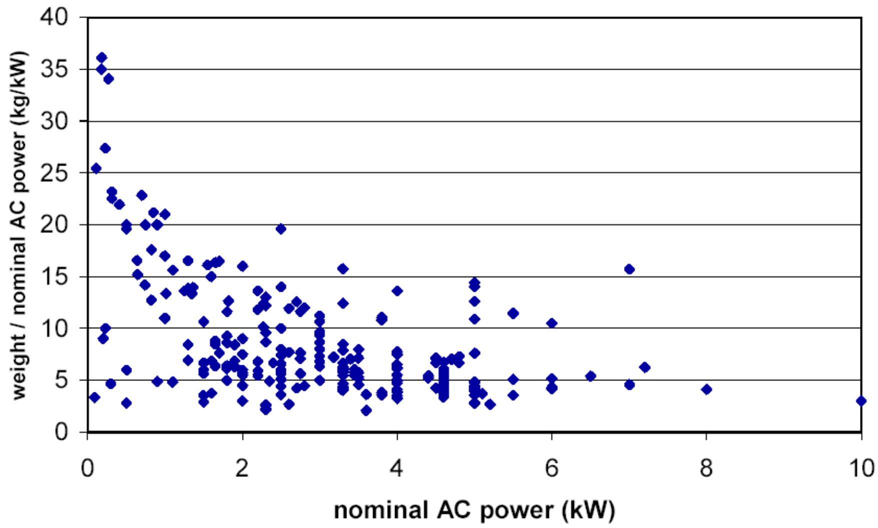


Fig. 10.4 Weight of small inverters (< 10 kW). Source: de Wild-Scholten et al. 2006

[41] Maximum-power–point-tracking is an electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power.

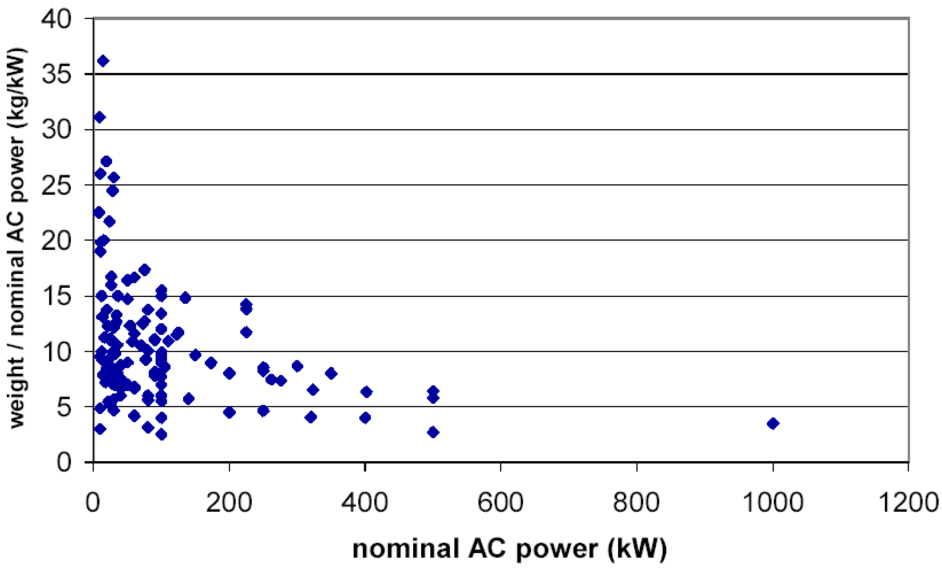


Fig. 10.5 Weight of large inverters (> 10kW). Source: (de Wild-Scholten et al. 2006)

Fig. 10.6 shows the interiors of a small-scale inverter (the PSI 300 from Phillips with a power of 300 W) with transformers, the different electronic parts and the case.

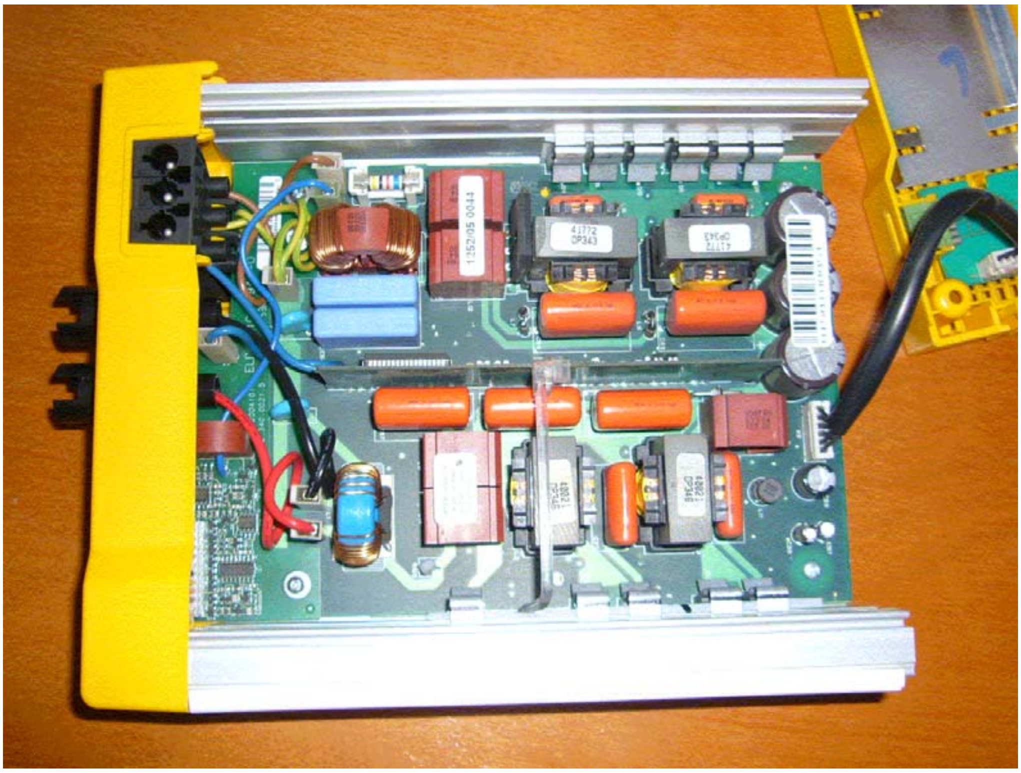


Fig. 10.6 Inside the inverter "PSI 300 from Phillips", Power 300 W. Source: (de Wild-Scholten et al. 2006)

10.9.2 Efficiency factor

The resulting efficiency of the inverter depends on different factors. Therefore one number does not represent the whole characteristic of an inverter under all circumstances (e.g. meteorological conditions, different voltage, MPP-Tracking). In order to achieve a practical value for calculating an average conversion factor, the follow approach has been chosen:

- Source of the values: the measurement of four tested inverter in the range from 2.5kW to 3.8 kW (Testing: Berner Fachhochschule, Informatik und Technik, Labs-Plattform / Photovoltaik, see Häberlin (2006))
- geometrical mean of the measured values (three different voltages) = measured total efficiency factor (see last column)
- geometrical mean of the four inverters

An average efficiency of 93.5% was taken for 500 W inverter and the 2500 W inverter (see Tab. 10.14). As the efficiency increase with the size of inverters, one has to consider the higher efficiency for the 500kW-inverter with an average of 95.4%.

Tab. 10.14: Total Efficiency factor for small-scale inverters

Model	Nominal power (kW)	Measured total Efficiency factor [1)]
Sunways NT4000	3.3	93.83
Fronius IG 40	3.5	91.53
Sputnik SM3000E	2.5	93.60
Sunnyboy 3800	3.8	94.97
Average	-	93.47

1) the efficiency factor is a product of the average European efficiency factor and the efficiency factor for the MPP Tracking, the measurement are from Häberlin (2006) and Kämpfer (2006)

Tab. 10.15 Total Efficiency factor for large-scale inverters of 250kW to 500kW

Model	Nominal power (kW)	European Efficiency factor [1)]	total Efficiency factor [2)]
SMA Sunny Central SC350	350	95.2	94.7
SMA Sunny Central SC500HE	500	97.3	96.8
SINVERT Solar 400, Siemens Automation & Drive	400	96	95.5
Solarmax 300C, Sputnik Engineering AG	400	94.8	94.3
Grid Tie Inverter GT500E, Xantrex 97%	500	97.3	96.8
Conergy IPG 280K, Conergy AG Deutschland	250	94.6	94.1
Geometric average			95.4

1) The european efficiency factor is a testscenario with determined radiation and simulates the meteorological conditions in Europe. The value is taken from the factsheets of each inverter.

2) The inverter has to maximise the MPP-tracking, in order to achieve a high efficiency under different conditions. The MPP-Efficiency ranges between 99.0 and 99.8%. Since only measurement from small-scale inverters are available (see Tab. 10.14), a fix MPP-efficiency of 99.5% has been taken for the 500kW-inverters.

10.9.3 Life cycle inventory of inverters

The life-cycle-inventories are mainly based on the reports of M. de Wild-Scholten (de Wild-Scholten & Alsema 2005; de Wild-Scholten et al. 2006), additional data about energy consumption and packaging is used from older literature (Schwarz & Keller 1992). Standard assumptions are taken for the transport of the materials and the disposal at the end-of-life.

Inverter, 500 W, at plant

De Wild-Scholten (2006) made a detailed investigation about an inverter with an output-power of 500 W (PSI 500 from Philips). The device mass is about 1.6 kg and consists mainly of electronic components and the case (Aluminium, Polycarbonate and ABS).

Inverter, 2500 W, at plant

Another investigated inverter (by Wild-Scholten (2006)) was the "Mastervolt Sunmaster 2500", produced by the German company "Mastervolt". The device mass is about 18.5 kg, with more than 50% w/w steel (from the casing) and about 35% transformers. Although this specific model is not anymore available on the market[42], the actual inverters have not changed their characteristics, as long as the weight is similar. The detailed list of electronic components from the inverter, 500 W (see Tab. 10.17) has been scaled up for the inverter, 2500W to a weight of 1.8kg of electronic components.

Inverter 500 kW, at plant

There is also an inventory from de Wild-Scholten (2006) available for an installation of a 1 MW-Inverter, based on Fthenakis (2006). The inventoried installation in Springerville, Arizona, US consists of 33 inverters (Xantrex 150-PV) with a reported mass of 20'000 kg per 1'000 kW Capacity. Since this mass-capacity-ratio is significant greater than the calculated ratios from actual inverters on the market (see Tab. 10.16), an adjustment has been made for the total mass: The used materials have been therefore scaled-down to the average size of actual inverter.

As on the market exists rarely inverters with a capacity greater than 500 kW (see Fig. 10.5), a down-scaling for an inverter with 500 kW has been made in this project (see Tab. 10.16).

Tab. 10.16 Weight and power capacity of several inverters

Model	Power-Capacity (kW)	Weight (kg)	Ratio (kg/kW)
SMA Sunny Central SC350	350	2800	8.0
SMA Sunny Central SC500HE	500	2200	4.4
SINVERT Solar 400, Siemens Automation & Drive	400	2600	6.5
Solarmax 300C, Sputnik Engineering AG	400	2600	6.5
Grid Tie Inverter GT500E, Xantrex 97%	500	1770	3.54
Conergy IPG 280K, Conergy AG Deutschland	250	2140	8.56
Geometric Mean	-	-	5.98

The calculation has been made for an inverter of 500kW power capacity with an average weight of 2991 kg (500kW * 5.98 kg/kW = 2991 kg).

[42] It is replaced with the models "Sunmaster QS 2000" and "Sunmaster QS 3200" of the same manufacturer "Mastervolt". These two products have a comparable power capacity.

Tab. 10.17 Components of Inverters, all data from de Wild-Scholten (2006)

Component	Unit	Inverter, 500W, at plant		Inverter, 2500W, at plant		Inverter, 500kW, at plant	
		Value	Remarks	Value	Remarks		Remarks
Aluminium	kg	0.682	casing	1.4	casing	131	c)
Polycarbonate	kg	0.068	casing	-			
ABS	kg	0.148	casing	-			
Poly Ethylene	kg	0.014		-	-		
PVC	kg	0.002	in cable	0.01	a)		
SAN (Styrene acrylonitrile)	kg	0.002	in cable	0.01	a)		
copper	kg	0.002	in cable	0.01	a)	335	c)
Steel	kg	0.078	screws and clamps	9.8		1438	c)
Printed Circuit Board	cm^2	596 b)	without components	2246	a)	2246	d)
connector	kg	0.050		0.237	a)	47.4	d)
transformers, wire-wound	kg	0.310		5.500			
coils	kg	0.074		0.351	a)	0.351	d)
IC's	kg	0.006		0.028	a)	0.028	d)
transistor	kg	0.008		0.038	a)	0.038	d)
transistor diode	kg	0.010		0.047	a)	0.047	d)
capacitor, film	kg	0.072		0.341	a)	0.341	d)
capacitor, electrolytic	kg	0.054		0.256	a)	0.256	d)
capacitor, CMC	kg	0.0048		0.023	a)	0.023	d)
resistors	kg	0.001		0.005	a)	0.005	d)
polyamide injection moulded	kg					71	c)
polyester	kg					44	c)
Polyethylene, HD	kg					22	c)
Paint	kg					22	c)
Transformer oil	kg					881	c)
Total	kg	1.673		18.5		2991	

a) up scaled from the 500W inverter, electronic data adjusted where data has been available

b) Weight is 500g

c) proportionally downscaled by this project from the 1MW-Inverter-Data of de Wild-Scholten (2007), but adjusted for the weight (see text)

d) Assumption: 500kW-Inverter has the same electronic components as the 2500W-Inverter, the size of connectors scale with capacity of inverter.

Packaging data (corrugated board, polystyrene foam and polyethylene-foil) have been taken from (Schwarz & Keller 1992), a correction was made for corrugated board, where the value seemed unrealistically high (2.5 kg of corrugated board instead of 6kg for the inverter of 18.5kg). The consumption of packaging material for the small-scale inverter and the 500 kW-inverter has been estimated on the base of the measured data of the mentioned 2.5 kW-inverter. Assuming a constant form and average density of the inverters, the wrapping packaging material is scaling up / down with the 3rd square root of the ratio of the masses. For the small-scale inverter of 0.5 kW a downscale-factor of 2.2 has been used, whereas the large-scale inverter needs 5.4-times more wrapping-material than the 2.5 kW-inverter.

According to Schwarz & Keller (1992), the electricity consumption for the assembling of an inverter of 20 kg is 22,9 kWh. Adapted to the weight of the investigated rectifiers, the consumption during production is 4.24 kWh for the 0.5 kW-Inverter, 21.2 kWh for the 2.5 kW-Inverter and 3600 kWh for the large scale-inverter of 500 kW.

Further information (e.g. emissions, plant-size) about the inverter production is not available.

Tab. 10.18 Energy consumption and packaging material for inverter, data from (Schwarz & Keller 1992),

	Unit	Inverter, 500W	Inverter, 2500W	Inverter, 500kW
corrugated board 1)	kg	1.12	2.5	13.6
polystyrene foam slab 1)	kg	0.13	0.3	1.6
polyethylene 1)	kg	0.03	0.06	0.3
Electricity 2)	kWh	4.24	21.2	4240

1) Scaling-Ratio for packaging: 2.2 (between 0.5kW-Inverter and 2.5kW-Inverter), 5.4 (between 2.5kW-Inverter and 500kW-Inverter), based on the 3rd root of mass ratios.

2) Scaling Ratio for electricity: 5 (between 0.5kW-Inverter and 2.5kW-Inverter), 200 (between 2.5kW-Inverter and 500kW-Inverter), based on the ratios of capacities.

Tab. 10.19 Unit process raw data for “Inverter, 500W, at plant” and “Inverter, 2500W, at plant”

	Name	Location	InfrastructureProcess	Unit	inverter, 500W, at plant	inverter, 2500W, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER			
	InfrastructureProcess				1	1			
	Unit				unit	unit			
product	inverter, 500W, at plant	RER	1	unit	1.00E+0	0			
product	inverter, 2500W, at plant	RER	1	unit	0	1.00E+0			
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	4.24E+0	2.12E+1	1	1.31	(2,3,4,1,1,5); Literature (Schwarz 1992)
	aluminium, production mix, cast alloy, at plant	RER	0	kg	6.82E-1	1.40E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), recycled after use
	copper, at regional storage	RER	0	kg	2.00E-3	5.51E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), recycled after use
	steel, low-alloyed, at plant	RER	0	kg	7.80E-2	9.80E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), recycled after use
	acrylonitrile-butadiene-styrene copolymer, ABS, at plant	RER	0	kg	1.48E-1	0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	polycarbonate, at plant	RER	0	kg	6.80E-2	0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.40E-2	0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	styrene-acrylonitrile copolymer, SAN, at plant	RER	0	kg	2.00E-3	1.00E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	polyvinylchloride, at regional storage	RER	0	kg	2.00E-3	1.00E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
electronical components	printed wiring board, through-hole, at plant	GLO	0	m2	5.96E-2	2.25E-1	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	transformer, high voltage use, at plant	GLO	0	kg	3.10E-1	0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	connector, clamp connection, at plant	GLO	0	kg	5.00E-2	2.37E-1	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	inductor, ring core choke type, at plant	GLO	0	kg	7.40E-2	3.51E-1	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	integrated circuit, IC, logic type, at plant	GLO	0	kg	6.00E-3	2.80E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	transistor, wired, small size, through-hole mounting, at plant	GLO	0	kg	8.00E-3	3.80E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	diode, glass-, through-hole mounting, at plant	GLO	0	kg	1.00E-2	4.70E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, film, through-hole mounting, at plant	GLO	0	kg	7.20E-2	3.41E-1	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, electrolyte type, > 2cm height, at plant	GLO	0	kg	5.40E-2	2.56E-1	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, Tantalum-, through-hole mounting, at plant	GLO	0	kg	4.80E-3	2.30E-2	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Assumption for Ceramic Multilayer Chip Capacitors
	resistor, metal film type, through-hole mounting, at plant	GLO	0	kg	1.00E-3	5.00E-3	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006), Calculation
processing	sheet rolling, steel	RER	0	kg	7.80E-2	9.80E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	wire drawing, copper	RER	0	kg	2.00E-3	5.51E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
	section bar extrusion, aluminium	RER	0	kg	6.82E-1	1.40E+0	1	1.22	(2,3,1,1,1,5); Literature (de Wild 2006)
infrastructure	metal working factory	RER	1	unit	1.04E-9	8.97E-9	1	3.06	(2,4,1,1,1,5); Calculation, based on annual production of electronic component production plant
packaging	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	1.12E+0	2.50E+0	1	1.24	(2,4,1,1,1,5); Calculation, based on estimated dimension of inverse rectifier
	polystyrene foam slab, at plant	RER	0	kg	1.30E-1	3.00E-1	1	1.31	(2,3,4,1,1,5); Literature (Schwarz 1992)
	fleece, polyethylene, at plant	RER	0	kg	3.00E-2	6.00E-2	1	1.31	(2,3,4,1,1,5); Literature (Schwarz 1992)
transport	transport, lorry >16t, fleet average	RER	0	tkm	3.66E-1	2.30E+0	1	2.09	(4,5,na,na,na,na); Standard distance 60km incl. disposal
	transport, freight, rail	RER	0	tkm	1.89E+0	7.11E+0	1	2.09	(4,5,na,na,na,na); Standard distances 200km
	transport, transoceanic freight ship	OCE	0	tkm	8.09E+0	3.63E+1	1	2.09	(4,5,na,na,na,na); Estimation: 18000km
emission air, high pop. dens.	Heat, waste	-	-	MJ	1.53E+1	7.63E+1	1	1.22	(2,3,1,1,1,5); Calculation
disposal	disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	0	kg	1.12E+0	2.50E+0	1	1.25	(2,3,1,5,1,5); Calculation, different geographical location
	disposal, polystyrene, 0.2% water, to municipal incineration	CH	0	kg	1.32E-1	3.10E-1	1	1.25	(2,3,1,5,1,5); Calculation, different geographical location
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	0	kg	3.00E-2	6.00E-2	1	1.25	(2,3,1,5,1,5); Calculation, different geographical location
	disposal, plastic, industr. electronics, 15.3% water, to municipal incineration	CH	0	kg	2.30E-1	0	1	1.25	(2,3,1,5,1,5); Calculation, different geographical location
	disposal, treatment of printed wiring boards	GLO	0	kg	6.90E-1	1.70E+0	1	1.25	(2,3,1,5,1,5); Calculation, different geographical location

Tab. 10.20 Unit process raw data for “Inverter, 500kW, at plant”

	Name	Location	InfrastructureProcess	Unit	inverter, 500kW, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				1			
	Unit				unit			
product	inverter, 500kW, at plant	RER	1	unit	1.00E+0			
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	4.58E+3	1	1.38	(4,3,4,1,1,5); Literature (Schwarz 1992)
	aluminium, production mix, cast alloy, at plant	RER	0	kg	1.31E+2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), recycled after use, Calculation
	copper, at regional storage	RER	0	kg	3.35E+2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), recycled after use, Calculation
	steel, low-alloyed, at plant	RER	0	kg	1.44E+3	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), recycled after use, Calculation
	polyethylene, HDPE, granulate, at plant	RER	0	kg	2.20E+1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	alkyd paint, white, 60% in solvent, at plant	RER	0	kg	2.20E+1	1	2.10	(4,3,1,1,5,5); Literature (de Wild 2006), Calculation
	lubricating oil, at plant	RER	0	kg	8.81E+2	1	2.10	(4,3,1,1,5,5); Literature (de Wild 2006), Calculation
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	7.10E+1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	glass fibre reinforced plastic, polyester resin, hand lay-up, at plant	RER	0	kg	4.40E+1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
electronical components	printed wiring board, through-hole, at plant	GLO	0	m2	2.25E-1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	connector, clamp connection, at plant	GLO	0	kg	4.74E+1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	inductor, ring core choke type, at plant	GLO	0	kg	3.51E-1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	integrated circuit, IC, logic type, at plant	GLO	0	kg	2.80E-2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	transistor, wired, small size, through-hole mounting, at plant	GLO	0	kg	3.80E-2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	diode, glass-, through-hole mounting, at plant	GLO	0	kg	4.70E-2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, film, through-hole mounting, at plant	GLO	0	kg	3.41E-1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, electrolyte type, > 2cm height, at plant	GLO	0	kg	2.56E-1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	capacitor, Tantalum-, through-hole mounting, at plant	GLO	0	kg	2.30E-2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	resistor, metal film type, through-hole mounting, at plant	GLO	0	kg	5.00E-3	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
processing	sheet rolling, steel	RER	0	kg	1.44E+3	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	injection moulding	RER	0	kg	7.10E+1	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	wire drawing, copper	RER	0	kg	3.35E+2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
	section bar extrusion, aluminium	RER	0	kg	1.31E+2	1	1.31	(4,3,1,1,1,5); Literature (de Wild 2006), Calculation
infrastructure	metal working factory	RER	1	unit	1.36E-6	1	3.10	(4,4,1,1,1,5); Calculation, based on annual production of electronic component production plant
packaging	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	1.36E+1	1	1.32	(4,4,1,1,1,5); Calculation, based on estimated dimension of inverse rectifier
	polystyrene foam slab, at plant	RER	0	kg	1.60E+0	1	1.38	(4,3,4,1,1,5); Literature (Schwarz 1992)
	fleece, polyethylene, at plant	RER	0	kg	3.00E-1	1	1.38	(4,3,4,1,1,5); Literature (Schwarz 1992)
transport	transport, lorry >16t, fleet average	RER	0	tkm	3.06E+2	1	2.09	(4,5,na,na,na,na); Standard distance 60km incl. disposal
	transport, freight, rail	RER	0	tkm	1.07E+3	1	2.09	(4,5,na,na,na,na); Standard distances 200km
	transport, transoceanic freight ship	OCE	0	tkm	1.04E+3	1	2.09	(4,5,na,na,na,na); Estimation: 18000km
emission air, high pop. dens.	Heat, waste	-	-	MJ	1.65E+4	1	1.31	(4,3,1,1,1,5); Calculation
disposal	disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	0	kg	1.36E+1	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location
	disposal, polystyrene, 0.2% water, to municipal incineration	CH	0	kg	1.60E+0	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	0	kg	1.60E+0	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location
	disposal, plastic, industr. electronics, 15.3% water, to municipal incineration	CH	0	kg	2.30E+2	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	8.81E+2	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location
	disposal, treatment of printed wiring boards	GLO	0	kg	4.89E+1	1	1.33	(4,3,1,5,1,5); Calculation, different geographical location

Tab. 10.21 shows the EcoSpold meta information of PV inverter production investigated in this chapter.

Tab. 10.21 EcoSpold meta information of PV inverters

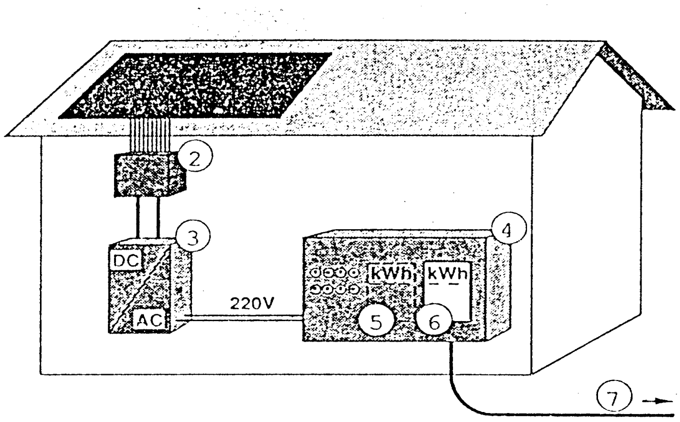
ReferenceFunction	Name	inverter, 500W, at plant	inverter, 2500W, at plant	inverter, 500kW, at plant
Geography	Location	RER	RER	RER
ReferenceFunction	InfrastructureProcess	1	1	1
ReferenceFunction	Unit	unit	unit	unit
DataSetInformation	Type	1	1	1
	Version	2.0	2.0	2.0
	energyValues	0	0	0
	LanguageCode	en	en	en
	LocalLanguageCode	de	de	de
DataEntryBy	Person	41	41	41
	QualityNetwork	1	1	1
ReferenceFunction	DataSetRelatesToProduct	1	1	1
	IncludedProcesses	Materials, packaging and electricity use for the production of an inverse rectifier. Disposal of the product after use.	Materials, packaging and electricity use for the production of an inverse rectifier. Disposal of the product after use.	Materials, packaging and electricity use for the production of an inverse rectifier. Disposal of the product after use.
	Amount	1	1	1
	LocalName	Wechselrichter, 500W, ab Werk	Wechselrichter, 2500W, ab Werk	Wechselrichter, 500kW, ab Werk
	Synonyms	inverse rectifier	inverse rectifier	inverse rectifier
	GeneralComment	Production of an inverter (500W) with an efficiency of 93.5% (total efficiency factor which includes MPP-Tracking) for photovoltaic plant. Total weight about 1.6 kg.	Production of an inverter (2500W) with an efficiency of 93.5% (total efficiency factor which includes MPP-Tracking) for photovoltaic plant. Total weight about 18.5 kg.	Production of an inverter (500kW) with an efficiency of 95.4% (total efficiency factor which includes MPP-Tracking) for photovoltaic plant. Total weight about 3000 kg.
	InfrastructureIncluded	1	1	1
	Category	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components
	LocalCategory	Photovoltaik	Photovoltaik	Photovoltaik
	LocalSubCategory	Herstellung Komponenten	Herstellung Komponenten	Herstellung Komponenten
TimePeriod	StartDate	2004	2004	2004
	EndDate	2006	2006	2006
	DataValidForEntirePeriod	1	1	1
Geography	Text	Production in RER.	Production in RER.	Production in RER.
Technology	Text	Inverter for a photovoltaic grid-connected system with a capacity of 500Wp.	Inverter for a photovoltaic grid-connected system with a capacity of 2.5kWp.	Inverter for a photovoltaic grid-connected system with a capacity of 500kWp.
	ProductionVolume	Not known.	Not known.	Not known.
	SamplingProcedure	Detailed analysis of materials for one product	Detailed analysis of materials for one product	Analysis of materials for a group of inverters, based on literature
	Extrapolations	Packaging materials and energy consumption during production has been scaled down from 2500 W-Inverter.	Data for electronic components has been extrapolated from 500 W-Inverter	Construction materials are extrapolated from a 1MW-Inverter included weight-adaptation, packaging materials have been scaled up from 2500 W-Inverter
	UncertaintyAdjustments	none	none	none
DataGenerator AndPublication	Person	41	41	41
	DataPublishedIn	2	2	2
	ReferenceToPublishedSource	24	24	24
	Copyright	1	1	1
	AccessRestrictedTo	0	0	0
ProofReading	Validator	57	57	57
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none

10.10 Electric installation

10.10.1 Overview

The following chapter investigates the electric installation for a photovoltaic power plant. This includes all installations between the panel and the grid, but not the inverter. A terminal box is not used anymore. The single parts of the installation are shown in Fig. 10.7.

In a first approximation, most of the material use can be assumed to be proportional to the installed capacity <Meier 1993>. An important factor is the size of the building and thus the distance between the PV-panels and the electricity grid. All data are investigated by Schwarz et al. (1992) with some own modifications. It was not possible to fully update these data for the present report.



Legend:
1. PV panels
2. (terminal box) (not used anymore)
3. inverter
4. fuse box
5. new electric meter
6. electric meter for grid electricity
7. public electricity grid.

(Source: <Prinz et al. 1992>)

Fig. 10.7 Illustration of electric installation of a PV power plant (partly outdated)

10.10.2 Electric cables and lightning arrester

Tab. 10.22 shows the material use for the electric cables and the lightning arrester. A set of panels of the PV plant is serial connected, connected with the inverter and this connected to the fuse box. The whole cabling of a 3 kW_p plant needs about 200 to 400 m of a 2 - 2.5 mm^2 copper wire <Meier 1993>.

At the inverter the electricity is transformed to alternating current (AC). Three thin cables (2.5 mm^2) connect the inverter with the 220 V cable to the electric meter and than with the grid.

An important issue is the lightning arrester. Different technical requirements are discussed (Häberlin 1991). Panel frames and mounting structure are connected by copper cable with the normal lightning arrester of the house. A length of 10 m copper wire (2.5 kg) is assumed. A 25 mm^2-cable is recommended for the grounding (Häberlin 1991). It is assumed that an existing lightning arrester of the building can be used. Thus an additional cable is laid from the fuse box to the electric meter (16 mm^2 Cu). The distance is assumed to be 10 m (2.3 kg copper).

The grounding cable between inverter and electric meter is 8 m long 25 mm^2-copper wire (1.8 kg).

Tab. 10.22 Material use for the electric installations (Schwarz & Keller 1992). Copper cables are used for the lightning arrester. Data for the area (e.g. 25 mm2 Cu) are related to the cross section surface of the cable.

Part of installation	Material	Mass
		kg
Lightning protection PV-plant	copper (28 mm^2 Cu)	2.5
Cabling PV panel area	wire (245 m): copper	4.66
	Radox 125	5.39
	PVC-isolation tube (9 m)	2.13
	cable clip(plastics)	0.32
	cable lug (copper)	0.11
Fuse box	copper	0.31
	steel	0.77
	plastics	1.34
	brass	0.02
	Polycarbonate	0.20
	Polyamide	0.23
	ZnO	0.04
	Epoxy (Lack)	0.002
	Radox 125	0.02
PV panels to inverter	wire (10m): copper	1.82
	Radox 125	2.69
	protection (copper)	0.97
	plastic tape	0.03
	cable lug Noryl (10m)	3.60
	grounding wire (10m): copper (16 mm^2 + 10 mm^2 Cu)	2.3
	Radox 125	0.30
	heat shrink tube (20cm): PE	0.02
	nail dowel: PE	0.16
Inverter to electric meter	grid cable (5m): copper	0.25
	Thermoplastic	0.17
	grounding wire (8m): copper (25 mm^2 Cu)	1.76
	Radox 125	0.32
	switch: copper	0.02
	plastics	0.07
	steel	0.09
Total		32.612

10.10.3 Life cycle inventory of the electric installation

Tab. 10.23 shows the unit process raw data of the electric installation derived from Tab. 10.22. Process data of the electric equipment include construction materials, wire drawing and transport services. The Radox-cable cladding is estimated with HDPE-plastic.

Recent, but rough data have been investigated in the CrystalClear project (de Wild-Scholten et al. 2006). An update of the material data has not been made for this study because of the small relevance for the total system and the comparable weight of materials. The data are not a production average, but an example for a possible installation. The energy use for the manufacturing of the mounting structures is not considered.

Tab. 10.23 Unit process raw data of the electric installation for a 3 kW$_p$ plant

	Name	Location	InfrastructureProcess	Unit	electric installation, photovoltaic plant, at plant	UncertaintyType	StandardDeviation	GeneralComment	de Wild 2006
	Location				CH				
	InfrastructureProcess				1				
	Unit				unit				unit
product	electric installation, photovoltaic plant, at plant	CH	1	unit	1.00E+0				
technosphere	copper, at regional storage	RER	0	kg	1.47E+1	1	1.24	(2,1,3,1,1,5); Literature, recycled after use	1.96E+1
	brass, at plant	CH	0	kg	2.00E-2	1	1.24	(2,1,3,1,1,5); Literature	
	zinc, primary, at regional storage	RER	0	kg	4.00E-2	1	1.24	(2,1,3,1,1,5); Literature	
	steel, low-alloyed, at plant	RER	0	kg	8.60E-1	1	1.24	(2,1,3,1,1,5); Literature, recycled after use	
	nylon 6, at plant	RER	0	kg	2.30E-1	1	1.24	(2,1,3,1,1,5); Literature	
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.76E+1	1	1.24	(2,1,3,1,1,5); Literature incl. different plastics and Radox insulation	1.45E+0
	polyvinylchloride, bulk polymerised, at plant	RER	0	kg	2.13E+0	1	1.24	(2,1,3,1,1,5); Literature	3.35E-1
	polycarbonate, at plant	RER	0	kg	2.00E-1	1	1.24	(2,1,3,1,1,5); Literature	
	epoxy resin, liquid, at plant	RER	0	kg	2.00E-3	1	1.24	(2,1,3,1,1,5); Literature	
manufacturing	wire drawing, copper	RER	0	kg	1.47E+1	1	1.24	(2,1,3,1,1,5); Assumption	
transport	transport, lorry 20-28t, fleet average	CH	0	tkm	2.15E+0	1	2.09	(4,5,na,na,na,na); Standard distance 60km incl. disposal	
	transport, freight, rail	CH	0	tkm	1.34E+1	1	2.09	(4,5,na,na,na,na); Standard distances 200km (metals 600km)	
disposal	disposal, plastic, industr. electronics, 15.3% water, to municipal incineration	CH	0	kg	2.02E+1	1	1.24	(2,1,3,1,1,5); Estimation	
	disposal, building, electric wiring, to final disposal	CH	0	kg	6.00E-2	1	1.24	(2,1,3,1,1,5); Estimation	
	total weight			kg	35.8				21.4

10.11 Meta information of balance of system

Tab. 10.24 shows the EcoSpold meta information of balance of system components investigated in this chapter.

Tab. 10.24 EcoSpold meta information of balance of system components

ReferenceFunction	Name	electric installation, photovoltaic plant, at plant	facade construction, mounted, at building	facade construction, integrated, at building	flat roof construction, on roof	slanted-roof construction, mounted, on roof	slanted-roof construction, integrated, on roof
Geography	Location	CH	RER	RER	RER	RER	RER
ReferenceFuncti	InfrastructureProcess	1	1	1	1	1	1
ReferenceFuncti	Unit	unit	m2	m2	m2	m2	m2
	IncludedProcesses	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use.	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.	Materials and packaging for the production and estimation for metal processing. Disposal of the product after use. Energy use for the construction process must be included in data for the PV-plant.
	LocalName	Elektroinstallationen, Photovoltaikanlage, ab Werk	Fassadenkonstruktion, aufgesetzt, an Gebäude	Fassadenkonstruktion, integriert, an Gebäude	Flachdachkonstruktion, auf Dach	Schrägdachkonstruktion, aufgesetzt, auf Dach	Schrägdachkonstruktion, integriert, auf Dach
	Synonyms						
	GeneralComment	Production of different components of the electric installation for a 3kWp photovoltaic plant.	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.	Production of the additional components necessary for the mounting of 1 m2 PV panel or laminate.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components	production of components	production of components	production of components
	Formula						
	StatisticalClassification						
	CASNumber						
TimePeriod	StartDate	1992	1992	1992	1992	1992	1992
	EndDate	1992	2008	2008	2008	2008	2008
	OtherPeriodText	Date of data investigation.	Date of data investigation. Actual weight of materials updated in 2008.	Date of data investigation. Actual weight of materials updated in 2008.	Date of data investigation. Actual weight of materials updated in 2008.	Date of data investigation. Actual weight of materials updated in 2008.	Date of data investigation. Actual weight of materials updated in 2008.
Geography	Text	Production in CH.	Production in CH.	Production in CH.	Production in CH.	Production in CH.	Production in CH.
Technology	Text	All electric installations for a photovoltaic system with a capacity of 3kWp. Including cables, counter, etc.	Construction parts for a photovoltaic system.	Construction parts for a photovoltaic system.	Construction parts for a photovoltaic system.	Construction parts for a photovoltaic system.	Construction parts for a photovoltaic system.
Representativeness	Percent	5	10	10	10	10	10
	ProductionVolume	Not known.	Not known.	Not known.	Not known.	Not known.	Not known.
	SamplingProcedure	Detailed analysis of materials for one product in a diploma thesis.	Detailed analysis of materials for one product in a diploma thesis.	Detailed analysis of materials for one product in a diploma thesis.	Detailed analysis of materials for one product in a diploma thesis.	Detailed analysis of materials for one product in a diploma thesis.	Detailed analysis of materials for one product in a diploma thesis.
	Extrapolations	none	From one product to the whole market. Correction factor applied to correct for today average weight per m2.	From one product to the whole market. Correction factor applied to correct for today average weight per m2.	From one product to the whole market. Correction factor applied to correct for today average weight per m2.	From one product to the whole market. Correction factor applied to correct for today average weight per m2.	From one product to the whole market. Correction factor applied to correct for today average weight per m2.

11 3 kWp PV power plants

11.1 Introduction

Combining the data for the single components derives the unit process raw data for the 3kWp PV power plants. The main parts are the PV-panels or laminates, the mounting structure, the inverter and the electric installation (Fig. 11.1). The inventory is supplemented with data for transports of panels, inverter and electric installation and with the energy use for the construction process according to the investigation in the previous chapter. It has to be noted that the transport of the mounting structure is already included in the unit process raw data investigated for this part, while all other transports and the energy use for the construction process is included in the unit process raw data investigated in this chapter.

All four main unit processes include the material uses, emissions and process energies per unit. Data for the dismantling and disposal are already included. The reference flow for the unit process raw data of 3kW$_p$ plants is one unit. By combination of the different types of panels and mounting structure we investigate 14 different types of plants (Tab. 3.2).

The operation of the plants with the electricity production is investigated in the following chapter.

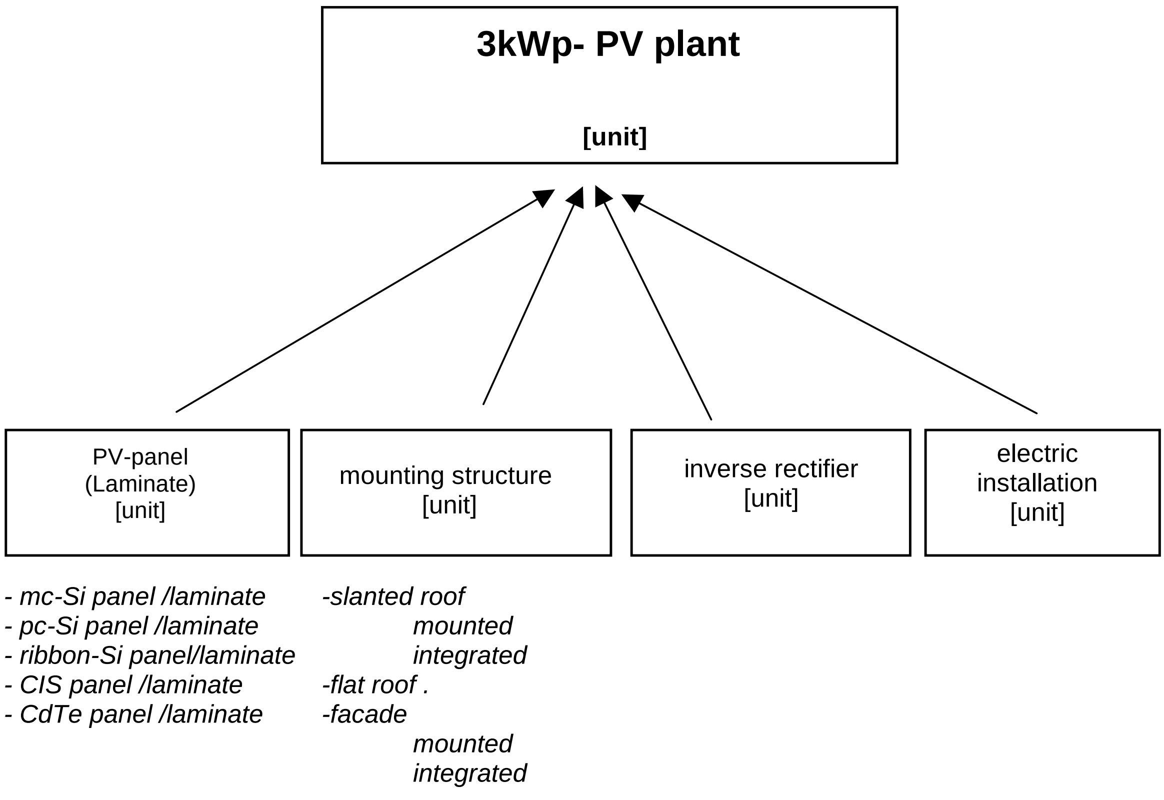


Fig. 11.1 Combination of unit process raw data for the PV-power plants. The four main modules of the life cycle inventory are combined.

11.2 Efficiency of solar cells

11.2.1 Developments

The efficiency of solar cells is measured under standardized conditions and describes the ratio of light converted to electricity. In order to calculate the amount of panels per installed kW_p it is necessary to know the efficiency of the solar cells and panels. Solar panels have a little bit lower efficiency then solar cells because of the area covered by the frame and gaps between the solar cells. The efficiencies have been optimized in the last years. They are also an important part of the information for the customer.

Fig. 11.2 shows the development of the maximum efficiencies of different types of solar cells over the last decades. One can observe a steady improvement of the cell efficiencies.

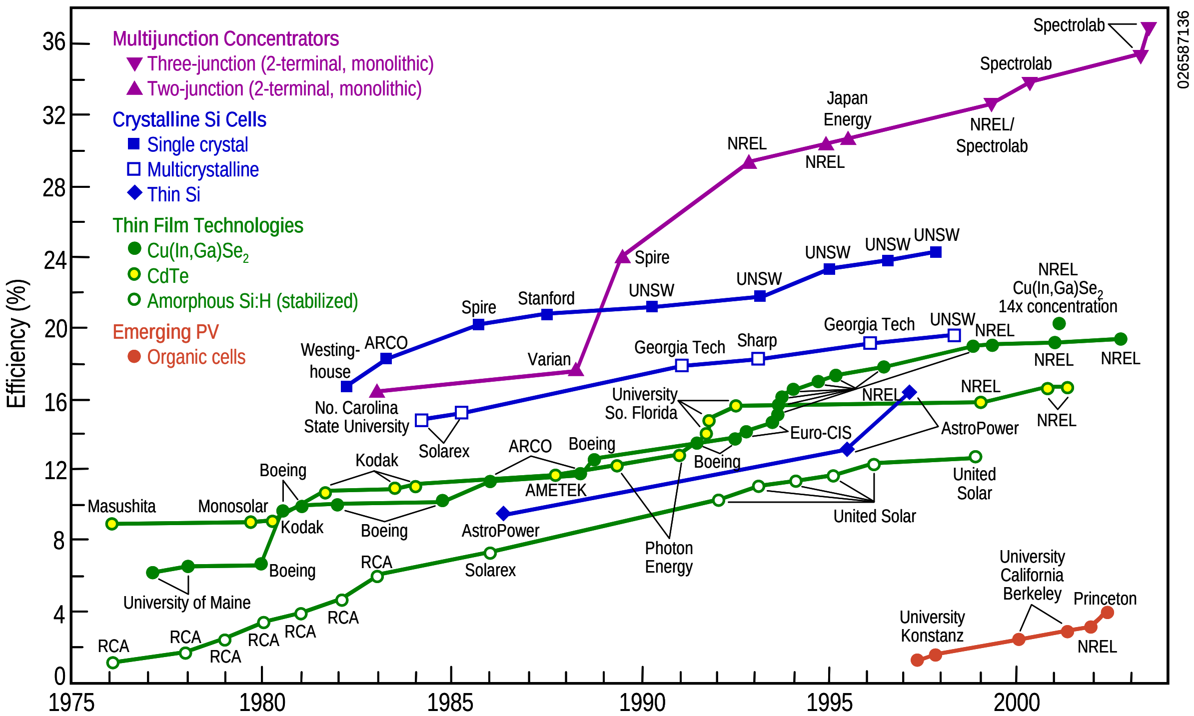


Fig. 11.2 Best research efficiencies. (NREL – National Renewable Energy Laboratory)[43]

In Fig. 11.3 we show a summary of efficiency data investigated over the past years and estimations for future improvements (here assigned to 2010). Tab. 11.1 shows a detailed summary of the available information. It has to be noted that there might be partly different assumptions behind these figures, which cannot be discussed for this overview in detail. Figures for panels are multiplied with a factor of 1.1 for calculating the cell efficiency. This factor has been estimated based on the ratio between active area and panel surface area in Tab. 11.2.

There is a large variation in the data for the cell efficiencies. Furthermore a slight trend for more efficient cells can be observed over the past years. On the other side it seems that earlier forecasts for the improvement were normally to optimistic. Maximum efficiencies from laboratory experiments are considered for the year 2020 (Lauinger 2000).

[43] Download on www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt, 6.2007.

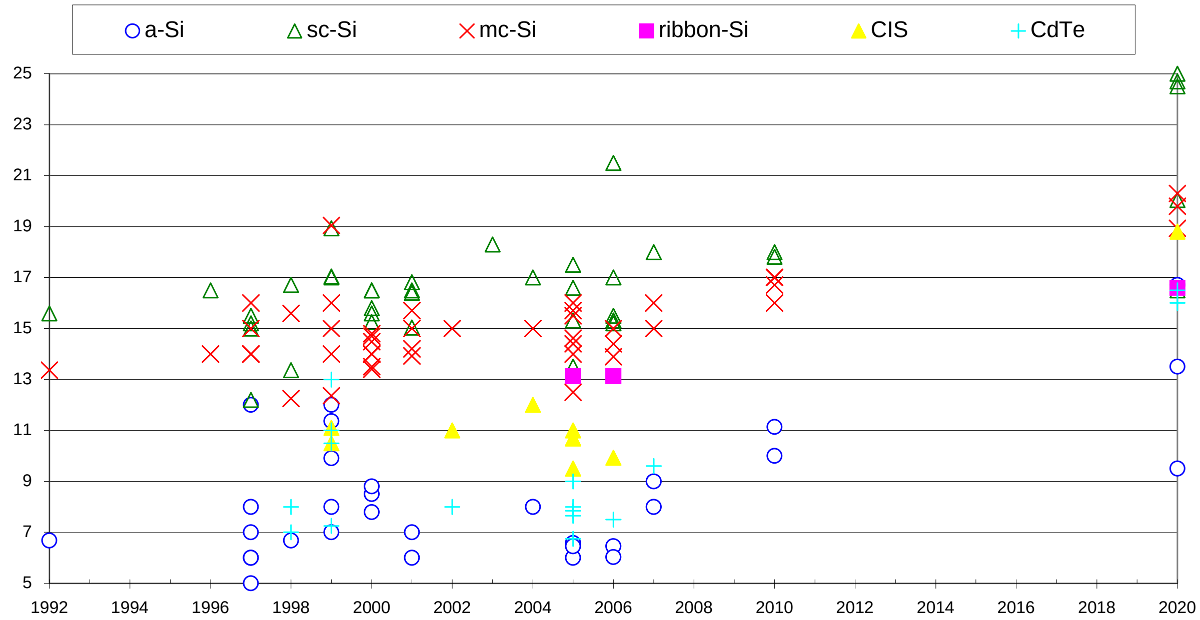


Fig. 11.3 Overview about the development of the efficiency for PV cells according to literature and information of producers

Tab. 11.1 shows the efficiencies of solar cells and photovoltaic panels reported in different studies. The different figures are sorted by the time of investigation. The values have been used for the summary in Fig. 11.3. Readers who are interested in a detailed understanding of all differences are referred to the original publications.

Tab. 11.1 Development of cell efficiencies and efficiencies of PV panels according to different assumptions in literature.

Type	C/P	- 1992	1993-97	1998 - 2000	2007	2010-20	Source
sc-Si	P	14					(Hagedorn & Hellriegel 1992)
	C/P		12.2-15.2/ 10.5-13.5				(Kohake 1997)
	C/P		15/12.3				(Kato et al. 1997b)
	C/P		15.5/12.7		18/14.8	18/14.8	(Alsema 1998; Alsema et al. 1998; Frankl & Gamberale 1998)
	P		16.5				(Frischknecht et al. 1996)
	P		12-15			24.5 [1])	(Munro & Rudkin 1999)
	P			15.3-17			(Fritsche & Lenz 2000)
	P			14		16-18	(Alsema 2000a)
	C			17			Shell solar D
	C					24.7	(Green et al. 2006)
mc-Si	P	12					(Hagedorn & Hellriegel 1992)
	C/P		14/12.1		16/ 13.8		(Alsema 1998; Alsema et al. 1998)
	C/P		14/12.1			16/14.5	(Frankl & Gamberale 1998)
	P		14				(Frischknecht et al. 1996)
	C/P		15-16/ 11.6-15.7	15-16/ 11.9-13.2			(Kato et al. 1997b) / (Kato 2000)
	P		11-14			19.8 [1])	(Munro & Rudkin 1999)
	P			11.1-17.1			(Fritsche & Lenz 2000)
	C			14			Shell solar D
	P			13		15-17	(Alsema 2000a)
	C					20.3	(Green et al. 2006)
a-Si	P	6					(Hagedorn & Hellriegel 1992)
	P		8-12	8-12			(Kato et al. 1997b) / (Kato 2000)
	C/P		-/6		-/9		(Alsema et al. 1998)
	P		6			10	(Frankl & Gamberale 1998)
	P		6-7			13.5 [1])	(Munro & Rudkin 1999)
	P			8.9-10.2			(Fritsche & Lenz 2000)
	C			7			Shell solar D
	P			5	8		(Lewis & Keoleian 1997)
	P			7		10-15	(Alsema 2000a)
	C					9.5	(Green et al. 2006)
CdTe	P		7-8			16.0 [1])	(Munro & Rudkin 1999)
CdTe				7.25-10.5			(Fritsche & Lenz 2000)
	C					16.5	(Green et al. 2006)
CdTe/ CdS	C/P			11-13/ 10.3-12.4			(Kato 2000)
CuInSe2				10.5-11.1			(Fritsche & Lenz 2000)
	C					18.8	(Green et al. 2006)

P Panel
C Cell
[1]) Maximum for cells in laboratory experiments

11.2.2 Efficiencies in this study

The cell efficiencies used in this study are shown in Tab. 11.2. The estimation for the silicon type based cells is based on a recent estimate based on extensive literature survey for the panel market in the year 2005 (de Wild-Scholten & Alsema 2007). The efficiency for CdTe cells has been taken from producers' information (Fthenakis & Kim 2005). The average of different literature data has been assumed for the CIS cells.

11.3 Amount of panels for a 3 kW_p PV plant

The amount of panels necessary for a 3 kW_p plant has to be calculated with the cell efficiency and the cell surface of the panel. The surface areas for a 3 kWp-plant are shown in Tab. 11.2. For a-Si and CIS there is no "cell" as such. Thus, the area of cell and panel is the same. Also the efficiency is not differentiated. Thus, it is the same for cell and panel

Tab. 11.2 Active panel area of 3 kWp-PV plants with different types of solar cells, cell efficiencies and calculated panel capacity, amount of panels per 3kW_p plant

cell type	cell efficiency	panel efficiency	cell area	cells	amount of panels per 3 kWp	active surface	panel capacity rate
	%	%	cm2	unit/m2	m2	m2	Wp/m2
sc-Si	15.3%	14.0%	243	37.6	21.4	19.6	140
mc-Si	14.4%	13.2%	243	37.6	22.8	20.8	132
ribbon-Si	13.1%	12.0%	243	37.6	25.0	22.9	120
a-Si	6.5%	6.5%	10000	1	46.5	46.5	65
CIS	10.7%	10.7%	10000	1	28.1	28.1	107
CdTe	9.0%	9.0%	10000	1	33.3	33.3	90

11.4 Dismantling of PV-power plants

For the dismantling of photovoltaic power plants standard scenarios used in the ecoinvent project according to the list of materials have been taken into account. For larger metal parts of the system and silicon a recycling is assumed. Neither environmental burdens nor credits have been considered for the recycling. In the production processes such materials are also used without a burden from the primary production process. So far no recycled silicon from PV panels has been used in the year 2005 nor it has been considered in the inventory herewith. The remaining parts are incinerated or land filled. Data are included within the individual unit process raw data investigated in this chapter.

11.5 Meta information of 3 kW_p power plants

Tab. 11.3 show the EcoSpold meta information of some of the 3 kW_p power plants investigated in this chapter, as examples.

Tab. 11.3 EcoSpold meta information of 3 kW_p power plants. Example for some plants

ReferenceFunction	Name	3kWp facade installation, single-Si, laminated, integrated, at building	3kWp facade installation, single-Si, panel, mounted, at building	3kWp facade installation, multi-Si, laminated, integrated, at building	3kWp facade installation, multi-Si, panel, mounted, at building
Geography	Location	CH	CH	CH	CH
ReferenceFuncti	InfrastructureProcess	1	1	1	1
ReferenceFuncti	Unit	unit	unit	unit	unit
	IncludedProcesses	All components for the installation of a 3kWp photovoltaic plant, energy use for the mounting, transport of materials and persons to the construction place. Disposal of components after end of life.	All components for the installation of a 3kWp photovoltaic plant, energy use for the mounting, transport of materials and persons to the construction place. Disposal of components after end of life.	All components for the installation of a 3kWp photovoltaic plant, energy use for the mounting, transport of materials and persons to the construction place. Disposal of components after end of life.	All components for the installation of a 3kWp photovoltaic plant, energy use for the mounting, transport of materials and persons to the construction place. Disposal of components after end of life.
	LocalName	3kWp Fassadenanlage, single-Si, laminiert, integriert, an Gebäude	3kWp Fassadenanlage, single-Si, Paneel, aufgesetzt, an Gebäude	3kWp Fassadenanlage, multi-Si, laminiert, integriert, an Gebäude	3kWp Fassadenanlage, multi-Si, Paneel, aufgesetzt, an Gebäude
	Synonyms	monocrystalline//single crystalline//silicon	monocrystalline//single crystalline//silicon	polycrystalline//multi-crystalline//silicon	polycrystalline//multi-crystalline//silicon
	GeneralComment	Photovoltaic installation with a capacity of 3kWp and a life time of 30 years installed in CH.	Photovoltaic installation with a capacity of 3kWp and a life time of 30 years installed in CH.	Photovoltaic installation with a capacity of 3kWp and a life time of 30 years installed in CH.	Photovoltaic installation with a capacity of 3kWp and a life time of 30 years installed in CH.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	production of components	production of components	production of components	production of components
	Formula				
	StatisticalClassification				
	CASNumber				
TimePeriod	StartDate	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005
	OtherPeriodText	Calculation of amount of panels used based on efficiency data for 2005. Other data are adopted.	Calculation of amount of panels used based on efficiency data for 2005. Other data are adopted.	Calculation of amount of panels used based on efficiency data for 2005. Other data are adopted.	Calculation of amount of panels used based on efficiency data for 2005. Other data are adopted.
Geography	Text	Installation in CH	Installation in CH	Installation in CH	Installation in CH
Technology	Text	Current technology for mounting of panels or laminates, electric installations and other components.	Current technology for mounting of panels or laminates, electric installations and other components.	Current technology for mounting of panels or laminates, electric installations and other components.	Current technology for mounting of panels or laminates, electric installations and other components.
Representativen	Percent	50	50	50	50
	ProductionVolume	Total installed capacity in 2000: 12.7MWp in CH. GLO installed PV-power 711MWp	Total installed capacity in 2000: 12.7MWp in CH. GLO installed PV-power 711MWp	Total installed capacity in 2000: 12.7MWp in CH. GLO installed PV-power 711MWp	Total installed capacity in 2000: 12.7MWp in CH. GLO installed PV-power 711MWp
	SamplingProcedure	Publication for efficiency, mounting systems and own estimations for other components.	Publication for efficiency, mounting systems and own estimations for other components.	Publication for efficiency, mounting systems and own estimations for other components.	Publication for efficiency, mounting systems and own estimations for other components.
	Extrapolations	Rough assumption for the decrease in material weights for mounting structures.	Rough assumption for the decrease in material weights for mounting structures.	Rough assumption for the decrease in material weights for mounting structures.	Rough assumption for the decrease in material weights for mounting structures.

11.6 Life cycle inventory of 3 kW_p PV plants

Tab. 11.4, Tab. 11.5 and Tab. 11.6 show the unit process raw data of 3kW_p PV plants. The delivery of the different plant parts to the final construction place is assumed with 100 km by a delivery van. This includes the transport of the construction workers. It is assumed that 20% of the panels are produced overseas and thus must be imported to Europe by ship. The lifetime of the inverter is assumed with 15 years. Thus, it must be exchanged once during the lifetime of the plant. The inverter investigated for this study has a capacity of 2.5 kW. Thus, a factor of 1.25 has been used for the 3kW$_p$ plant.

Also for the PV panels a 2% replacement of damaged modules during the lifetime plus a further production loss during handling of 1% is assumed here. The electricity use for mounting is considered in this inventory as well. For the use of mounting structures shown in Tab. 11.6, it is considered that the thin film cells have a lower efficiency and thus more panels need to be installed. This has been considered with a factor calculated from the panel area for specific plant.

The data quality for the PV panels and laminates is quite good for characterizing plants manufactured in Europe. A range of different studies and recent data from producers could be used for the different production stages. The data quality for the different parts of the plant is quite different. The data for the mounting structure are quite detailed. They have been updated at least for the weight of materials. It was necessary to introduce a correction factor that accounts only for the change in the weight of packaging materials.

The data of the inverters used here have been updated for this study. Thus, they can be considered reliable. The relevance of the electric installation is small and not so much changes are expected for these older data.

Tab. 11.4 Unit process raw data of 3kW$_p$ sc-Silicon plants

	Name	Location	InfrastructureProcess	Unit	3kWp facade installation, single-Si, laminated, integrated, at building	3kWp facade installation, single-Si, panel, mounted, at building	3kWp flat roof installation, single-Si, on roof	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	UncertaintyType	StandardDeviation95%	GeneralComment	weight	electricity /3kWp
	Location				CH	CH	CH	CH	CH					
	InfrastructureProcess				1	1	1	1	1					
	Unit				unit	unit	unit	unit	unit				*kg*	*kWh*
technosphere	electricity, low voltage, at grid	CH	0	kWh	4.00E-2	4.00E-2	1.02E+0	2.30E-1	2.30E-1	1	1.28	(3,4,3,1,1,5); Energy use for erection of 3kWp plant		
	inverter, 2500W, at plant	RER	1	unit	2.40E+0	2.40E+0	2.40E+0	2.40E+0	2.40E+0	1	1.24	(2,4,1,1,1,na); Literature, 1 repair in the life time	18.5	
	electric installation, photovoltaic plant, at plant	CH	1	unit	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1	2.09	(3,4,3,1,1,5); Literature	35.8	
	facade construction, mounted, at building	CH	1	m2	-	2.14E+1	-	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x	0.04
	facade construction, integrated, at building	CH	1	m2	2.14E+1	-	-	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x	0.04
	flat roof construction, on roof	CH	1	m2	-	-	2.14E+1	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x	1.02
	slanted-roof construction, mounted, on roof	CH	1	m2	-	-	-	-	2.14E+1	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x	0.23
	slanted-roof construction, integrated, on roof	CH	1	m2	-	-	-	2.14E+1	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x	0.23
	photovoltaic laminate, single-Si, at plant	RER	1	m2	2.21E+1	-	-	2.21E+1	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	12.0	
	photovoltaic panel, single-Si, at plant	RER	1	m2	-	2.21E+1	2.21E+1	-	2.21E+1	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	14.6	
	operation, lorry 20-28t, empty, fleet average	CH	0	vkm	-	-	8.00E+1	-	-	1	2.09	(3,4,3,1,1,5); crane 80km to construction place		
	transport, van <3.5t	CH	0	tkm	3.45E+1	4.03E+1	4.03E+1	3.45E+1	4.03E+1	1	2.09	(3,4,3,1,1,5); electric parts and panel 100km to construction place		
	transport, lorry >16t, fleet average	RER	0	tkm	1.33E+2	1.62E+2	1.62E+2	1.33E+2	1.62E+2	1	2.09	(3,4,3,1,1,5); 500km for import of panels and laminates to Switzerland		
	transport, transoceanic freight ship	OCE	0	tkm	5.30E+2	6.46E+2	6.46E+2	5.30E+2	6.46E+2	1	2.09	(3,4,3,1,1,5); 2000km for import (20%) of panels and laminates to Switzerland		
emission air	Heat, waste	-	-	MJ	1.44E-1	1.44E-1	3.67E+0	8.28E-1	8.28E-1	1	1.28	(3,4,3,1,1,5); calculated with electricity use		

Tab. 11.5 Unit process raw data of 3kW$_p$ mc-silicon PV plants

	Name	Location	InfrastructureProcess	Unit	3kWp facade installation, multi-Si, laminated, integrated, at building	3kWp facade installation, multi-Si, panel, mounted, at building	3kWp flat roof installation, multi-Si, on roof	3kWp slanted-roof installation, multi-Si, laminated, integrated, on roof	3kWp slanted-roof installation, multi-Si, panel, mounted, on roof	UncertaintyType	StandardDeviation95%	GeneralComment	weight
	Location				CH	CH	CH	CH	CH				
	InfrastructureProcess				1	1	1	1	1				
	Unit				unit	unit	unit	unit	unit				*kg*
technosphere	electricity, low voltage, at grid	CH	0	kWh	4.00E-2	4.00E-2	1.02E+0	2.30E-1	2.30E-1	1	1.28	(3,4,3,1,1,5); Energy use for erection of 3kWp plant	
	inverter, 2500W, at plant	RER	1	unit	2.40E+0	2.40E+0	2.40E+0	2.40E+0	2.40E+0	1	1.24	(2,4,1,1,1,na); Literature, 1 repair in the life time	18.5
	electric installation, photovoltaic plant, at plant	CH	1	unit	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1	2.09	(3,4,3,1,1,5); Literature	35.8
	facade construction, mounted, at building	CH	1	m2	-	2.28E+1	-	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x
	facade construction, integrated, at building	CH	1	m2	2.28E+1	-	-	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x
	flat roof construction, on roof	CH	1	m2	-	-	2.28E+1	-	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x
	slanted-roof construction, mounted, on roof	CH	1	m2	-	-	-	-	2.28E+1	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x
	slanted-roof construction, integrated, on roof	CH	1	m2	-	-	-	2.28E+1	-	1	1.23	(3,1,1,1,1,na); calculation with m2 panel	x
	photovoltaic laminate, multi-Si, at plant	RER	1	m2	2.35E+1	-	-	2.35E+1	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	12.0
	photovoltaic panel, multi-Si, at plant	RER	1	m2	-	2.35E+1	2.35E+1	-	2.35E+1	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	14.6
	operation, lorry 20-28t, empty, fleet average	CH	0	vkm	-	-	8.00E+1	-	-	1	2.09	(3,4,3,1,1,5); crane 80km to construction place	
	transport, van <3.5t	CH	0	tkm	3.62E+1	4.24E+1	4.24E+1	3.62E+1	4.24E+1	1	2.09	(3,4,3,1,1,5); electric parts and panel 100km to construction place	
	transport, lorry >16t, fleet average	RER	0	tkm	1.41E+2	1.72E+2	1.72E+2	1.41E+2	1.72E+2	1	2.09	(3,4,3,1,1,5); 500km for import of panels and laminates to Switzerland	
	transport, transoceanic freight ship	OCE	0	tkm	5.64E+2	6.87E+2	6.87E+2	5.64E+2	6.87E+2	1	2.09	(3,4,3,1,1,5); 2000km for import (20%) of panels and laminates to Switzerland	
emission air	Heat, waste	-	-	MJ	1.44E-1	1.44E-1	3.67E+0	8.28E-1	8.28E-1	1	1.28	(3,4,3,1,1,5); calculated with electricity use	

Tab. 11.6 Unit process raw data of 3kW$_p$ other PV plants

	Name	Location	InfrastructureProcess	Unit	3kWp slanted-roof installation, CIS, panel, mounted, on roof	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	UncertaintyType	StandardDeviation95%	GeneralComment	weight
	Location				CH	CH	CH	CH	CH	CH				
	InfrastructureProcess				1	1	1	1	1	1				
	Unit				unit	unit	unit	unit	unit	unit				*kg*
technosphere	electricity, low voltage, at grid	CH	0	kWh	4.00E-2	4.00E-2	4.00E-2	4.00E-2	4.00E-2	4.00E-2	1	1.28	(3,4,3,1,1,5); Energy use for erection of 3kWp plant	
	inverter, 2500W, at plant	RER	1	unit	2.40E+0	2.40E+0	2.40E+0	2.40E+0	2.40E+0	2.40E+0	1	1.24	(2,4,1,1,1,na); Literature, 1 repair in the life time	18.5
	electric installation, photovoltaic plant, at plant	CH	1	unit	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1	2.09	(3,4,3,1,1,5); Literature	35.8
	slanted-roof construction, mounted, on roof	RER	1	m2	2.81E+1	2.50E+1	-	-	-	4.65E+1	1	1.23	(3,1,1,1,1,na); New estimation with mean value of frame weights, correction for panel area	x
	slanted-roof construction, integrated, on roof	RER	1	m2	-	-	3.33E+1	2.50E+1	4.65E+1	-	1	1.23	(3,1,1,1,1,na); New estimation with mean value of frame weights, correction for panel area	x
	photovoltaic laminate, ribbon-Si, at plant	RER	1	m2	-		-	2.58E+1	-	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	12.0
	photovoltaic panel, ribbon-Si, at plant	RER	1	m2	-	2.58E+1	-	-	-	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	14.6
	photovoltaic laminate, a-Si, at plant	US	1	m2	-	-	-	-	4.79E+1	-	1	2.09	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	2.7
	photovoltaic panel, a-Si, at plant	US	1	m2	-	-	-	-	-	4.79E+1	1	2.09	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	8.2
	photovoltaic panel, CIS, at plant	DE	1	m2	2.89E+1	-	-	-	-	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	17.6
	photovoltaic laminate, CdTe, mix, at regional storage	RER	1	m2	-	-	3.43E+1	-	-	-	1	1.36	(3,4,3,1,1,5); Calculation, 2% of modules repaired in the life time, 1% rejects	20.7
	operation, lorry 20-28t, empty, fleet average	CH	0	vkm	-	-	-	-	-	-	1	2.09	(3,4,3,1,1,5); crane 80km to construction place	
	transport, van <3.5t	CH	0	tkm	5.90E+1	4.57E+1	7.91E+1	3.89E+1	2.09E+1	4.74E+1	1	2.09	(3,4,3,1,1,5); electric parts and panel 100km to construction place	
	transport, lorry >16t, fleet average	RER	0	tkm	2.55E+2	1.88E+2	3.55E+2	1.55E+2	6.46E+1	1.97E+2	1	2.09	(3,4,3,1,1,5); 500km for import of panels and laminates to Switzerland	
	transport, transoceanic freight ship	OCE	0	tkm	1.02E+3	7.54E+2	-	6.19E+2	2.58E+2	7.87E+2	1	2.09	(3,4,3,1,1,5); 2000km for import (20%) of panels and laminates to Switzerland	
emission air	Heat, waste	-	-	MJ	1.44E-1	1.44E-1	1.44E-1	1.44E-1	1.44E-1	1.44E-1	1	1.28	(3,4,3,1,1,5); calculated with electricity use	

12 Operation of photovoltaic power plants

12.1 Annual output in different countries

12.1.1 Switzerland

The actual electricity yield of PV plants is quite dependent on the annual irradiation at the place of installation. The irradiation depends on local and regional sunshine and weather conditions. This varies in Switzerland between 1110 kWh/m^2 (Olten) and 1530 kWh/m^2 (Jungfraujoch) (4 - 5.5 GJ/m^2). The average solar irradiation in Switzerland is about 1100 kWh per m^2 and year.

The annual yield per kW_p can be estimated based on experiences. Such estimation for different regions in Switzerland is shown in Tab. 12.1. The yield at the best location in Switzerland might be twice this of the worst one. This underlines the importance of the choice for the location of a PV plant. These estimation already considers the losses due to the use of inverters.

Tab. 12.1 Estimation for the annual yield per installed kW_p capacity for different regions in Switzerland (Häberlin 1991, <Aufdenblatten et al. 1996>)

site of the plant	Yield
	kWh/a kWp
Midland (misty, non-optimum orientation)	520 - 700
Midland (good location and orientation)	700 - 880
Southern Switzerland and foothills of the alps	790 - 1140
Alpine areas	1230 - 1760

All yield data for recent years are shown in Tab. 12.2 (Hostettler 2006; Meier et al. 2000; Meier et al. 2001). The photovoltaic plants in operation in Switzerland show an average electricity production of 820 kWh per kW_p for the years 2000 to 2005. Due to changing meteorological conditions the annual yields ranged between 770 and 880 kWh per kW_p.

Tab. 12.2 Mean electricity production of PV plants in Switzerland (Hostettler 2006; Meier et al. 2000; Meier et al. 2001)

year	**Output grid-connected** kWh/kW_p
1992	800
1993	810
1994	800
1995	815
1996	825
1997	880
1998	858
1999	770
2000	810
2001	800
2002	800
2003	875
2004	815
2005	820
Mean (2000-2005)	**820**

Fig. 12.1 shows the distribution of yields for the year 2005. It is obvious that the average yield is decreased due to some installations with a quite low performance. The publication (Gaiddon & Jedliczka 2006) calculates for plants located in Bern an annual yield of 922 and 620 kWh/kW_p for roof-top and

façade installations, respectively. This yield is calculated with an irradiation of 1117 kWh per m^2 and a performance ratio of 0.75, which results in an average yield of 892 kWh/kW_p (average of all roof-top and façade installations). Details about the calculation of figures for roof-top and façade installations are not provided in the study, but it can be assumed that the angle and orientation have been taken into account.

Actually the performance ratio in Switzerland seems to be lower than assumed in the calculation of (Gaiddon & Jedliczka 2006). The IEA-PVPS Task 2 published a figure of 0.694, which would result in an average yield of 775 kWh/kW_p, but this statistical figure takes into account only about 13% of the PV installations in Switzerland.[44]

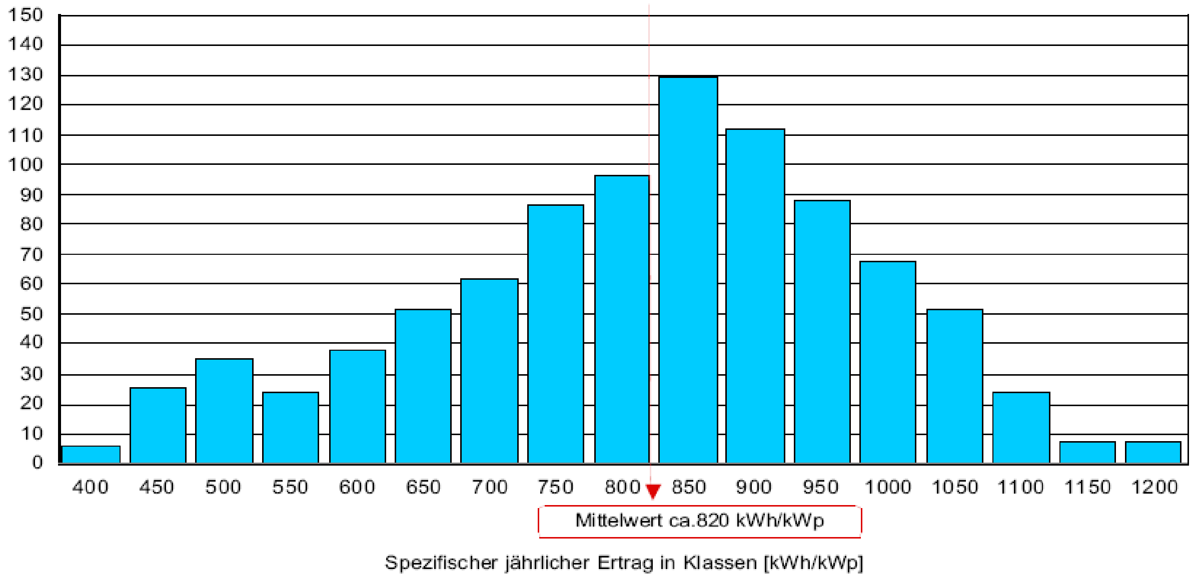


Fig. 12.1 Annual yield of PV-power plants in Switzerland in the year 2005. Number of plants per class. Mean figure is 820 kWh/kWp (Hostettler 2006)

Tab. 12.3 shows the different possibilities how to estimate the yield of PV-plants. From Fig. 12.1 it is estimated that most of PV plants achieve a yield of about 850 kWh/kW_p (Median). It can be concluded that there is a quite important difference between the actually achieved average yield and the yield of PV-power plants, which are installed in optimum orientation and operated under optimum conditions. The average yield is considerably lower than what can be expected for an operation under good conditions.

Here we take the figure of 820 kWh per kW_p as the basis to calculate the yield in the photovoltaic power mix in Switzerland. The PV electricity mix is used to calculate the country specific electricity mixes in the ecoinvent database.

For the analysis of different PV technologies it would not be fair to include also existing installations with a very low performance into account. Thus, the analysis of different technologies e.g. roof-top and façade installations is based on the approach using the performance according to (Gaiddon & Jedliczka 2006) as a basis of the yield calculation. The share of façade installation in this is assumed with 10%.

In any case an analysis of PV electricity should clearly state whether average operation or optimum operation is the baseline.

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44 www.task2.org, www.iea-pvps.org

Tab. 12.3 Calculation of electricity yields (kWh/kW$_p$) based on average performance, performance of good plants and optimum conditions. Estimation of the yield in this study. *Cursive figures partly based on own assumptions*

	This study	minimum	average 2000-2005	median	build in 2006	state of the art	optimum
average	*820*		*820*	850	*892*		
Roof-Top	*922*		*848*	*880*	922	950	1200
Facade	*620*	400	*568*	*580*	620		
		Hostettler 2006	*own calculation*	*Hostettler 2006*	*Gaiddon 2006*	*Nowak 2007*	*Hostettler 2006*

Sources: (Gaiddon & Jedliczka 2006; Hostettler 2006), Nowak 2007: Personal communication, 6.2007

12.1.2 International

The yield per kW$_p$ is one important factor for the comparison of PV with other types of electricity production. The yield is quite dependent on the solar irradiation and thus on the location of the installation (see Fig. 12.2). Here we investigate the PV electricity mixes for several European countries with the specific yields for each country. Also non-European countries (e.g. from Africa, the Americas, etc.) are considered for such a calculation as far as data for the yield is available.

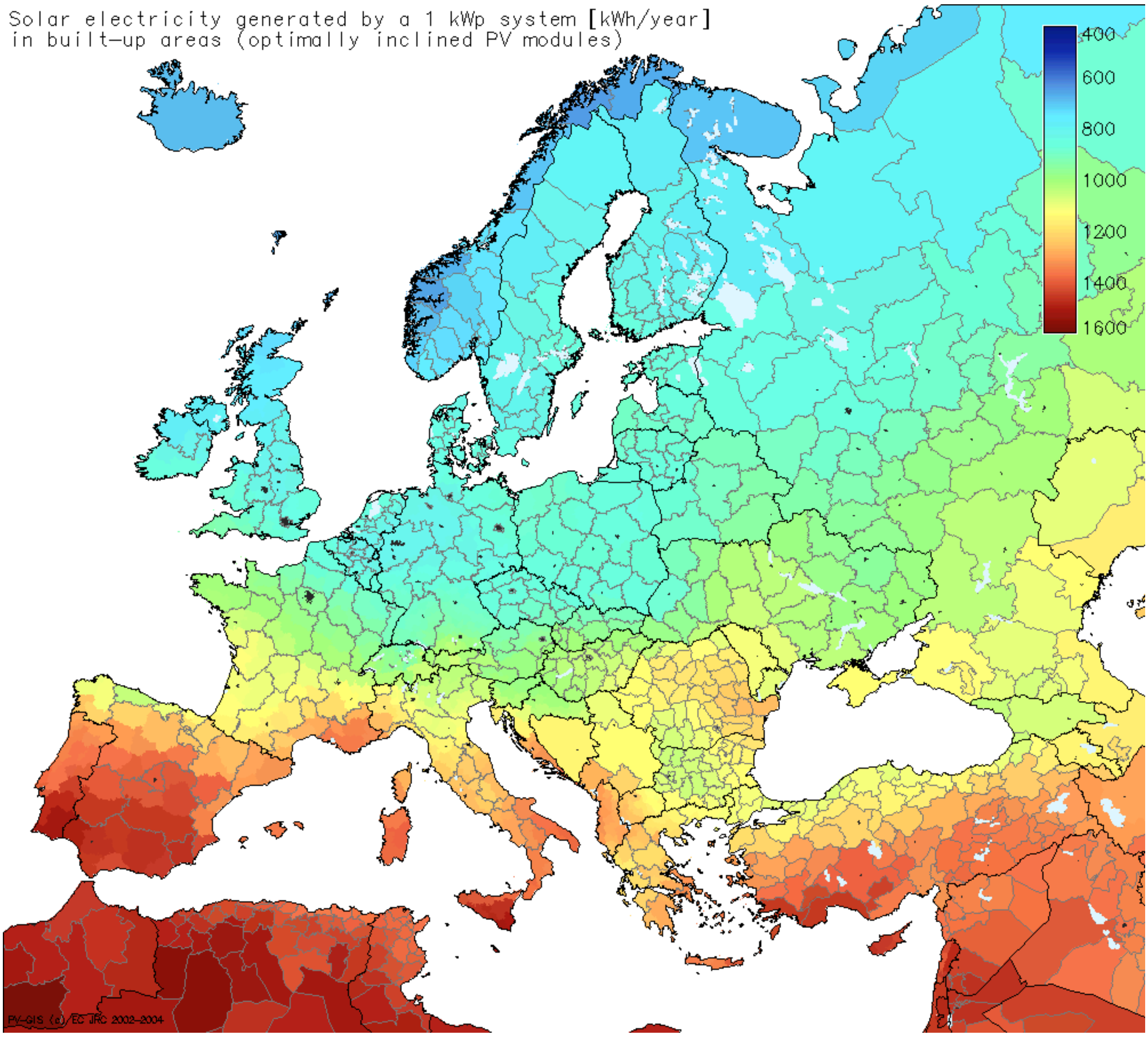

Fig. 12.2 Solar electricity generated by a 1 kW$_p$ system (kWh/year) in built-up areas (http://re.jrc.ec.europa.eu/pvgis/index.htm)

The calculations for international electricity production with PV-power plants are based on annual output data published by the IEA (Gaiddon & Jedliczka 2006). The data for the annual output of rooftop and façade PV-power plants in Tab. 12.4 describe the yield of newly erected plants.

In order to take into account the lower average yield as observed in Switzerland (see discussion in the previous chapter) we introduced a correction factor of 92%. This is based on the ratio of actual yield and the published IEA data as shown in Tab. 12.3 (820/892 = 0.92). The corrected annual output data for slanted-roof and façade installations have been used to calculate the amount of power plant necessary for the production of one kWh of electricity. For all countries shown in this table an electricity production mix with PV power plants has been estimated.

As discussed in section 12.1.1, the yield data from this publication describe now an average installation.

The calculation does not take into account possible variations for the actual production patterns in different stages of production. As the conditions investigated for Switzerland can be assumed to be fairly representative also for the European market possible deviations are not considered to be very important compared to the influence of the yield. For Asia and Americas the used data for the PV plants can only be considered as a rough assumption.

Tab. 12.4 Global horizontal irradiation and annual output for roof-top and façade PV power plants in different countries. Calculation based on average performance ratio of 0.75 corrected with the average yield data in Switzerland as shown in the two last columns (Gaiddon & Jedliczka 2006)

		Global horizontal irradiation kWh/m2	Annual output, Roof-Top kWh/kWp	Annual output, Facade kWh/kWp	Performance ration Roof-Top	Performance ratio Facade	**Annual output, Roof-Top, corrected kWh/kWp**	**Annual output, Facade, corrected kWh/kWp**
Austria	AT	1'108	906	598	82%	54%	833	550
Belgium	BE	946	788	539	83%	57%	725	496
Czech Republic	CZ	1'000	818	548	82%	55%	752	504
Denmark	DK	985	850	613	86%	62%	782	564
Finland	FI	956	825	602	86%	63%	759	554
France	FR	1'204	984	632	82%	52%	905	581
Germany	DE	972	809	561	83%	58%	744	516
Greece	GR	1'563	1'278	774	82%	50%	1'175	712
Hungary	HU	1'198	988	656	82%	55%	908	603
Ireland	IE	948	811	583	86%	61%	746	536
Italy	IT	1'251	1'032	676	82%	54%	949	622
Japan	JP	1'168	955	631	82%	54%	878	580
Luxembourg	LU	1'035	862	582	83%	56%	793	535
Netherlands	NL	1'045	886	611	85%	58%	815	562
Norway	NO	967	870	674	90%	70%	800	620
Portugal	PT	1'682	1'388	858	83%	51%	1'276	789
Spain	ES	1'660	1'394	884	84%	53%	1'282	813
Sweden	SE	980	860	639	88%	65%	791	588
Switzerland	CH	1'117	922	620	83%	56%	848	570
United Kingdom	GB	955	788	544	83%	57%	725	500
United States	US	1'816	1'512	913	83%	50%	1'390	839
Australia	AU	1'686	1'315	721	78%	43%	1'209	663
Canada	CA	1'273	1'088	735	85%	58%	1'000	676
Korea, Republic Of	KR	1'215	1'002	674	82%	55%	921	620
New Zealand	NZ	1'412	1'175	762	83%	54%	1'080	701
Turkey	TR	1'697	1'400	840	82%	49%	1'287	772

12.2 Lifetime for PV plants

In the year 2005 some older PV power plants have been dismantled and replaced with new plants (Jauch & Tscharner 2006). The lifetime of PV-plants produced today can only be estimated. Panels have normally a guarantee time of 10 to 20-years given by the manufacturer. Also for economic calculations a lifetime of 20 years is assumed. In LCA case studies the lifetime has been assumed between 20 and 30 years. A lifetime of 30 years seems to be realistic according to the available information.[45] So far it is not clear if the lifetime for new thin film technologies might be longer or shorter. A lifetime of 30 years has been assumed for this study for all types of technologies (de Wild-Scholten & Alsema 2007). Within this calculation it is also taken into account that a part of the panels and necessary infrastructure must be replaced during this lifetime because of failures.

A decreased yield over the lifetime is taken into account with the yield data, which are based on production statistics in Tab. 12.2. But, it is not assumed that especially a-silicon based PV plants are replaced earlier than other types of PV plants.

[45] „Aufgrund der bisherigen Erfahrungen mit netzgekoppelten PV Anlagen, die zurzeit im Maximum bereits 20 Jahre in Betrieb sind, kann davon ausgegangen werden, dass mit entsprechendem Unterhalt eine Lebensdauer von 30 Jahren erreicht wird. Entsprechender Unterhalt heisst, dass nach ca. 15 Jahren der Wechselrichter revidiert oder ausgetauscht wird, und dass ev. vereinzelt Module mit Schäden ausgetauscht werden müssen, und dass auch die Verkabelung periodisch kontrolliert und bei Bedarf z.B. Klemmen ausgetauscht werden müssen. Von der Modulseite her kann mit den aktuellen Garantiebedingungen der meisten Hersteller (min. 80% Leistung nach 20 Jahren Betrieb) eine 30-jährige Lebensdauer erwartet werden. Module, die sich nach 20 Jahren noch in einwandfreiem Zustand befinden werden noch weitere Jahre problemlos funktionieren, Module mit Herstellungs- oder Materialfehlern müssen auf Garantie ausgetauscht werden.“ Personal communication Stephan Gnos, NET AG, CH, 10.2002.

12.3 Emissions during operation

PV-plants do normally not show any emissions to air or water during operation. The emissions due to maintenance operations are already considered in the inventories of the single components. Some panels might be washed by the user on an annual basis. Here we assume the use of 20 litre water per year and square meter for the washing of the panels (Frischknecht et al. 1996). Wastewater will be discharged with the normal rainwater and its treatment is accounted for.

Diffuse metal emissions due to corrosion of frame materials are not taken into account. They are mainly possible if the metals get into contact with salts, e.g. if they are located near a street were salt is used in the winter time.

12.4 Waste heat

A PV panel might emit surplus waste heat compared to the situation without such an installation. The normal albedo[46] might be reduced and more irradiation is transferred into heat. The sun has produced the heat itself and thus there is no change in the total balance. But, on a local scale the heat formation might be higher and thus there might be a small rise in local temperature.

The reflection of light to the sky or to neighbouring buildings is not accounted for in the ecoinvent data. A disturbance of neighbouring buildings might occur due to such reflections.

Roesler <1992> has compared the waste heat emissions from a possible PV plant with a parking area of the similar size. He estimated that a small influence on the local climate might be possible. This might be mainly important for large-scale plants, e.g. in dessert areas.

The albedo of a PV plant can be compared with other types of surfaces. Such figures are shown in Tab. 12.5. The albedo of PV panels is calculated according to <Shah et al. 1990> with the assumption that a panel absorbs 75% of the irradiation. About 6%-15% of the total irradiation are transformed to electricity depending on the type of PV technology. The rest is transformed into heat which is normally dissipated by convection. Also the delivered electricity will result in the emission of waste heat during its transport and at use. Thus, 25% of the irradiation are not absorbed. This figure can now be compared with the albedo observed before installation of the PV plant. The albedo of PV plants is in the same range as these of building materials. Thus the possible influence seems to be quite small. For plants on open ground the possible effect might not be neglected.

[46] Albedo is the ratio of the electromagnetic radiation power that is diffusively reflected to an observer to the incident electromagnetic radiation power.

Tab. 12.5 Some figures for the albedo of natural and anthropogenic-influenced surfaces <Goward 1987, Bariou et al. 1985, Schäfer 1985>

surface	albedo
	%
PV-plant	25
fresh snow	75-95
old snow	40-70
granite-rocks	31
coniferous forest	5-15
limestone rocks	36
leafed forest, meadows	10-20
paved road	5-10
cities	15-25
dry concrete	17-27
average on earth	34-42

We assume, along ecoinvent standard methodology, that the waste heat emissions due to the use of electricity are accounted for at the processes using the electricity. The part of irradiation not transformed to electricity is not taken into account as a waste heat emission during operation of the plant. The use of solar energy is calculated with the amount of electric energy delivered by the cell to the inverter. The average efficiency of solar inverters is 93.5% (see chapter 10.9.2). The use of "energy, solar" equals 3.6 MJ/kWh / 93.5% = 3.85 MJ/kWh. The waste heat directly released is 3.85 minus 3.6 = 0.25 MJ/kWh.

12.5 Land occupation

It is assumed that all PV plants investigated in this study are located on existing buildings. Thus no surplus land occupation is taken into account. The full land occupation is allocated to the building and thus to its normal use. Land occupation should be taken into account for plants on open-ground, which are not modelled in this study.

12.6 Accidents

The most important risks or accidents due to the operation of photovoltaics are according to <Tietze et al. 1989, Roesler et al. 1992> and (Fthenakis 2004) the following events:

- electric shock from power plant operation
- downfalls of maintenance workers at PV installations
- danger due to fires

Only fires are linked with the emission of relevant pollutants e.g. polyvinylfluoride. The danger of emissions due to fires is mainly discussed for new thin film materials containing cadmium or other hazardous substances, e.g. cells with CdS, CuS, $CuInSe_2$ and GaAs (Fthenakis 2004). So far statistical data or experimental measurements are not available. Thus emissions due to accidents are not considered for the life cycle inventory, because they do not appear frequently in operation.

12.7 Types of PV plants

For the electricity mix it is necessary to know which type of cells and installations is actually used for

PV-plants. The share of different types of cells installed world-wide is well known. The share of different types of photovoltaic cells is estimated in Tab. 12.6 based on Fig. 2.2 and further information.

Tab. 12.6 Share of different types of cells produced worldwide in 2005

	This study
single-Si	38.4%
multi-Si	52.4%
ribbon-Si	2.9%
a-Si	4.7%
CdTe	1.4%
CIS	0.2%
Total	100%

The share of different types of mounting systems is estimated in Tab. 12.7. The rough estimation is based on older literature data <SOFAS 1994> and recent expert guesses.[47]

Tab. 12.7 Share of different types of mounting systems for the total installed capacity

	CH	RER
façade installation, laminated, integrated, at building	5%	2.5%
façade installation, panel, mounted, at building	5%	10%
flat roof installation, on roof	15%	20%
slanted-roof installation, laminated, integrated, on roof	5%	2.5%
slanted-roof installation, panel, mounted, on roof	70%	65%
	100%	100%

Tab. 12.8 shows the actual mix used for different types of PV plants for the calculation of average electricity mixes. The shares are calculated from the information shown in Tab. 12.6 and Tab. 12.7.

47 Personal communication with Pius Hüsser, Novaenergie, CH, 16.12.2006

Tab. 12.8 Share of different types of cells and mounting systems for the calculation of average electricity mixes

	CH	RER
	%	%
3kWp facade installation, single-Si, laminated, integrated, at building	1.9%	1.0%
3kWp facade installation, single-Si, panel, mounted, at building	1.9%	3.8%
3kWp facade installation, multi-Si, laminated, integrated, at building	2.6%	1.3%
3kWp facade installation, multi-Si, panel, mounted, at building	2.6%	5.2%
3kWp flat roof installation, single-Si, on roof	5.8%	7.7%
3kWp flat roof installation, multi-Si, on roof	7.9%	10.5%
3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	1.9%	1.0%
3kWp slanted-roof installation, single-Si, panel, mounted, on roof	26.9%	25.0%
3kWp slanted-roof installation, multi-Si, laminated, integrated, on roof	2.6%	1.3%
3kWp slanted-roof installation, multi-Si, panel, mounted, on roof	36.6%	34.0%
3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	2.7%	2.8%
3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	0.2%	0.1%
3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	1.4%	1.4%
3kWp slanted-roof installation, CIS, panel, mounted, on roof	0.2%	0.2%
3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	0.3%	0.2%
3kWp slanted-roof installation, a-Si, panel, mounted, on roof	4.4%	4.5%
electricity, production mix photovoltaic, at plant	**100%**	**100%**

12.8 Life cycle inventories of PV-electricity production

The unit process raw data for the electricity production with different PV power plants in Switzerland is shown in Tab. 12.9. All inventory data have been discussed in the previous chapters. The amount of 3 kW_p units per kWh of electricity is calculated with the yield (Tab. 12.3), the lifetime of 30 years and the share of the specific type of installation. Water consumption (for cleaning the panels once a year) is included in the inventory. Due to the higher uncertainties for the yield, the basic uncertainty is estimated to be 1.2. A major factor for the performance is the lifetime of the PV plants, which can so far only be assessed.

Tab. 12.10 shows the unit process raw data for some other countries. This table does not show the data for all electricity mixes investigated for the database. The calculation is based on the yields shown in Tab. 12.4. This table however shows the full list of investigated electricity mixes.

Tab. 12.9 Unit process raw data of electricity production with single 3kW$_p$ PV plants in Switzerland

	Name	Location	Unit	electricity, PV, at 3kWp facade, single-Si, laminated, integrated	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted	electricity, PV, at 3kWp facade, multi-Si, laminated, integrated	electricity, PV, at 3kWp facade installation, multi-Si, panel, mounted	electricity, PV, at 3kWp flat roof installation, single-Si	electricity, PV, at 3kWp flat roof installation, multi-Si	electricity, PV, at 3kWp slanted-roof, single-Si, laminated, integrated	electricity, PV, at 3kWp slanted-roof, single-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, multi-Si, laminated, integrated	StandardDeviation95%	GeneralComment
	Location			CH	CH	CH	CH	CH	CH	CH	CH	CH		
	InfrastructureProcess			0	0	0	0	0	0	0	0	0		
	Unit			kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh		
resource, in air	Energy, solar, converted	-	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	1.09	(2,2,1,1,1,3); Energy loss in the system is included
technosphere	tap water, at user	CH	kg	7.68E-3	7.68E-3	8.17E-3	8.17E-3	5.16E-3	5.49E-3	5.16E-3	5.16E-3	5.49E-3	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	m3	7.68E-6	7.68E-6	8.17E-6	8.17E-6	5.16E-6	5.49E-6	5.16E-6	5.16E-6	5.49E-6	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	3kWp facade installation, single-Si, laminated, integrated, at building	CH	unit	1.79E-5	-	-	-	-	-	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	CH	unit	-	1.79E-5	-	-	-	-	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp facade installation, multi-Si, laminated, integrated, at building	CH	unit	-	-	1.79E-5	-	-	-	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp facade installation, multi-Si, panel, mounted, at building	CH	unit	-	-	-	1.79E-5	-	-	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	CH	unit	-	-	-	-	1.21E-5	-	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp flat roof installation, multi-Si, on roof	CH	unit	-	-	-	-	-	1.21E-5	-	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	CH	unit	-	-	-	-	-	-	1.21E-5	-	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	CH	unit	-	-	-	-	-	-	-	1.21E-5	-	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
	3kWp slanted-roof installation, multi-Si, laminated, integrated, on roof	CH	unit	-	-	-	-	-	-	-	-	1.21E-5	1.24	(3,2,1,1,1,3); yield at good installation, average is lower while optimum would be higher, basic uncertainty = 1.2
emission air	Heat, waste	-	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	1.05	(1,na,na,na,na,na); Calculation

Tab. 12.9 Unit process raw data of electricity production with single 3kWp PV plants in Switzerland (part 2)

	Name	Location	Unit	electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, ribbon-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, ribbon-Si, lam., integrated	electricity, PV, at 3kWp slanted-roof, CdTe, laminated, integrated	electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted	electricity, PV, at 3kWp slanted-roof, a-Si, lam., integrated	electricity, PV, at 3kWp slanted-roof, a-Si, panel, mounted	electricity, production mix photovoltaic, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH	CH	CH	CH	CH	CH	CH	CH			
	InfrastructureProcess			0	0	0	0	0	0	0	0			
	Unit			kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh			
resource, in air	Energy, solar, converted	-	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	1	1.09	(2,2,1,1,1,3); Energy loss in the system is included
technosphere	tap water, at user	CH	kg	5.49E-3	6.03E-3	6.03E-3	8.03E-3	6.77E-3	1.12E-2	1.12E-2	5.87E-3	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	m3	5.49E-6	6.03E-6	6.03E-6	8.03E-6	6.77E-6	1.121E-05	1.121E-05	5.87E-6	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	3kWp facade installation, single-Si, laminated, integrated, at building	CH	unit	-	-	-	-	-	-	-	3.76E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	CH	unit	-	-	-	-	-	-	-	3.76E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, multi-Si, laminated, integrated, at building	CH	unit	-	-	-	-	-	-	-	5.12E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, multi-Si, panel, mounted, at building	CH	unit	-	-	-	-	-	-	-	5.12E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	CH	unit	-	-	-	-	-	-	-	7.55E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, multi-Si, on roof	CH	unit	-	-	-	-	-	-	-	1.03E-6	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	CH	unit	-	-	-	-	-	-	-	2.52E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	CH	unit	-	-	-	-	-	-	-	3.53E-6	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, multi-Si, laminated, integrated, on roof	CH	unit	-	-	-	-	-	-	-	3.43E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, multi-Si, panel, mounted, on roof	CH	unit	1.21E-5	-	-	-	-	-	-	4.80E-6	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	CH	unit	-	1.21E-5	-	-	-	-	-	3.55E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	CH	unit	-	-	1.21E-5	-	-	-	-	2.54E-8	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	CH	unit	-	-	-	1.21E-5	-	-	-	1.84E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	CH	unit	-	-	-	-	1.21E-5	-	-	2.62E-8	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	CH	unit	-	-	-	-	-	1.21E-5	-	4.11E-8	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	CH	unit	-	-	-	-	-	-	1.21E-5	5.75E-7	1	1.24	(3,2,1,1,1,3); average yield, estimation for share of technologies. Basic uncertainty = 1.2
emission air	Heat, waste	-	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	1	1.05	(1,na,na,na,na,na); Calculation

Tab. 12.10 Unit process raw data of electricity production with 3kW$_p$ PV plants in different countries

	Name	Location	InfrastructureProcess	Unit	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				AT	BE	CZ	DK	FI	FR	DE	GR			
	InfrastructureProcess				0	0	0	0	0	0	0	0			
	Unit				kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh			
resource, in air	Energy, solar, converted	-	-	MJ	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	3.85E+0	1	1.09	(2,2,1,1,1,3); Calculation with average module efficiency
technosphere	tap water, at user	CH	0	kg	6.06E-3	6.93E-3	6.69E-3	6.37E-3	6.55E-3	5.61E-3	6.73E-3	4.36E-3	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.06E-6	6.93E-6	6.69E-6	6.37E-6	6.55E-6	5.61E-6	6.73E-6	4.36E-6	1	1.09	(2,2,1,1,1,3); Estimation 20l/m2 panel
	3kWp facade installation, single-Si, laminated, integrated, at building	CH	1	unit	1.94E-7	2.15E-7	2.12E-7	1.89E-7	1.93E-7	1.84E-7	2.07E-7	1.50E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, single-Si, panel, mounted, at building	CH	1	unit	7.77E-7	8.62E-7	8.48E-7	7.58E-7	7.72E-7	7.35E-7	8.28E-7	6.00E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, multi-Si, laminated, integrated, at building	CH	1	unit	2.64E-7	2.93E-7	2.89E-7	2.58E-7	2.63E-7	2.50E-7	2.82E-7	2.04E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp facade installation, multi-Si, panel, mounted, at building	CH	1	unit	1.06E-6	1.17E-6	1.15E-6	1.03E-6	1.05E-6	1.00E-6	1.13E-6	8.17E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, single-Si, on roof	CH	1	unit	1.03E-6	1.18E-6	1.14E-6	1.09E-6	1.13E-6	9.44E-7	1.15E-6	7.27E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp flat roof installation, multi-Si, on roof	CH	1	unit	1.40E-6	1.61E-6	1.55E-6	1.49E-6	1.53E-6	1.29E-6	1.56E-6	9.90E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, laminated, integrated, on roof	CH	1	unit	1.28E-7	1.47E-7	1.42E-7	1.37E-7	1.41E-7	1.18E-7	1.44E-7	9.09E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, single-Si, panel, mounted, on roof	CH	1	unit	3.33E-6	3.83E-6	3.69E-6	3.55E-6	3.66E-6	3.07E-6	3.73E-6	2.36E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, multi-Si, laminated, integrated, on roof	CH	1	unit	1.75E-7	2.01E-7	1.93E-7	1.86E-7	1.92E-7	1.61E-7	1.95E-7	1.24E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, multi-Si, panel, mounted, on roof	CH	1	unit	4.54E-6	5.22E-6	5.03E-6	4.84E-6	4.98E-6	4.18E-6	5.08E-6	3.22E-6	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, panel, mounted, on roof	CH	1	unit	3.73E-7	4.29E-7	4.13E-7	3.97E-7	4.09E-7	3.43E-7	4.18E-7	2.64E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, ribbon-Si, laminated, integrated, on roof	CH	1	unit	1.43E-8	1.65E-8	1.59E-8	1.53E-8	1.57E-8	1.32E-8	1.61E-8	1.02E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CdTe, laminated, integrated, on roof	CH	1	unit	1.87E-7	2.15E-7	2.07E-7	1.99E-7	2.05E-7	1.72E-7	2.09E-7	1.33E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	CH	1	unit	2.67E-8	3.07E-8	2.96E-8	2.85E-8	2.93E-8	2.46E-8	2.99E-8	1.89E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, laminated, integrated, on roof	CH	1	unit	2.32E-8	2.67E-8	2.57E-8	2.48E-8	2.55E-8	2.14E-8	2.60E-8	1.65E-8	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
	3kWp slanted-roof installation, a-Si, panel, mounted, on roof	CH	1	unit	6.04E-7	6.95E-7	6.69E-7	6.44E-7	6.64E-7	5.56E-7	6.77E-7	4.28E-7	1	1.22	(2,2,1,1,1,3); Calculation with average annual output and share of technologies. Basic uncertainty = 1.2
emission air	Heat, waste	-	-	MJ	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	2.50E-1	1	1.05	(1,na,na,na,na,na); Calculation

	Unit	Austria	Belgium	Czech Republic	Denmark	Finland	France	Germany	Greece
Global horizontal irradiation	kWh/m2	1108	946	1000	985	956	1204	972	1563
Annual output, Roof-Top, corrected	kWh/kWp	833	725	752	782	759	905	744	1175
Annual output, Facade, corrected	kWh/kWp	550	496	504	564	554	581	516	712
Annual output, Roof-Top	kWh/kWp	906	788	818	850	825	984	809	1278
Annual output, Facade	kWh/kWp	598	539	548	613	602	632	561	774

12.9 Meta information of PV electricity production

Tab. 12.11 and Tab. 12.12 show an example for the EcoSpold meta information of PV electricity production investigated in this chapter.

Tab. 12.11 EcoSpold meta information of PV electricity production in Switzerland

ReferenceFunction	Name	electricity, PV, at 3kWp facade, single-Si, laminated, integrated	electricity, PV, at 3kWp facade installation, single-Si, panel, mounted	electricity, PV, at 3kWp facade, multi-Si, laminated, integrated	electricity, PV, at 3kWp facade installation, multi-Si, panel, mounted	electricity, PV, at 3kWp flat roof installation, single-Si
Geography	Location	CH	CH	CH	CH	CH
ReferenceFuncti	InfrastructureProcess	0	0	0	0	0
ReferenceFuncti	Unit	kWh	kWh	kWh	kWh	kWh
	IncludedProcesses	Infrastructure for 3kWp PV-plant. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Infrastructure for 3kWp PV-plant. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Infrastructure for 3kWp PV-plant. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Infrastructure for 3kWp PV-plant. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Infrastructure for 3kWp PV-plant. Water use for cleaning. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.
	LocalName	Strom, Photovoltaik, ab 3kWp, Fassade, single-Si, laminiert, integriert	Strom, Photovoltaik, ab 3kWp, Fassade, single-Si, Paneel, aufgesetzt	Strom, Photovoltaik, ab 3kWp, Fassade, multi-Si, laminiert, integriert	Strom, Photovoltaik, ab 3kWp, Fassade, multi-Si, Paneel, aufgesetzt	Strom, Photovoltaik, ab 3kWp, Flachdach, single-Si
	Synonyms	monocrystalline//single crystalline//silicon	monocrystalline//single crystalline//silicon	polycrystalline//multi-crystalline//silicon	polycrystalline//multi-crystalline//silicon	monocrystalline//single crystalline//silicon
	GeneralComment	Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries.	Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries.	Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries.	Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries.	Assumption for electricity production of photovoltaic plants with good performance. Average performance is lower while optimum performance would be higher. Total capacity in Switzerland for the year 2005 was 23.8 MWp. Dataset can be used for comparison of energy technologies in Switzerland, but not for assessment of average production patterns. Yield data must be corrected for the installations used in other countries.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	power plants	power plants	power plants	power plants	power plants
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	2005	2005	2005	2005	2005
	EndDate	2005	2005	2005	2005	2005
	OtherPeriodText	Calculation for yield based on production with a state of the art plant.	Calculation for yield based on production with a state of the art plant.	Calculation for yield based on production with a state of the art plant.	Calculation for yield based on production with a state of the art plant.	Calculation for yield based on production with a state of the art plant.
Geography	Text	Use in CH.	Use in CH.	Use in CH.	Use in CH.	Use in CH.
Technology	Text	Electricity production with grid-connected photovoltaic power plants integrated in buildings facade.	Electricity production with grid-connected photovoltaic power plants mounted on buildings facade.	Electricity production with grid-connected photovoltaic power plants integrated in buildings facade.	Electricity production with grid-connected photovoltaic power plants mounted on buildings facade.	Electricity production with grid-connected photovoltaic power plants mounted on buildings flat roof.
Representativen	Percent	100	100	100	100	100
	ProductionVolume	In 2005 there were 1900 PV-plants with an annual production of 17800MWh	In 2005 there were 1900 PV-plants with an annual production of 17800MWh	In 2005 there were 1900 PV-plants with an annual production of 17800MWh	In 2005 there were 1900 PV-plants with an annual production of 17800MWh	In 2005 there were 1900 PV-plants with an annual production of 17800MWh
	SamplingProcedure	Statistical data for CH.	Statistical data for CH.	Statistical data for CH.	Statistical data for CH.	Statistical data for CH.
	Extrapolations	none	none	none	none	none

Tab. 12.12 EcoSpold meta information of PV electricity mixes in different countries

ReferenceFunct ion	Name	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant
Geography	Location	CH	AT	NZ	BE	TR
ReferenceFuncti	InfrastructureProcess	0	0	0	0	0
ReferenceFuncti	Unit	kWh	kWh	kWh	kWh	kWh
	IncludedProcesses	Production mix of photovoltaic electricity in the country. Assumptions for share of different technologies. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Production mix of photovoltaic electricity in the country. Annual output, Roof-Top: 833, Annual output, Facade: 550 kWh/kWp. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Production mix of photovoltaic electricity in the country. Annual output, Roof-Top: 1080, Annual output, Facade: 701 kWh/kWp. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Production mix of photovoltaic electricity in the country. Annual output, Roof-Top: 725, Annual output, Facade: 496 kWh/kWp. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.	Production mix of photovoltaic electricity in the country. Annual output, Roof-Top: 1287, Annual output, Facade: 772 kWh/kWp. Amount of solar energy transformed to electricity. Waste heat emission due to losses of electricity in the system.
	LocalName	Strommix, Photovoltaik, ab Anlage	Strommix, Photovoltaik, ab Anlage	Strommix, Photovoltaik, ab Anlage	Strommix, Photovoltaik, ab Anlage	Strommix, Photovoltaik, ab Anlage
	Synonyms					
	GeneralComment	Average (2000-2005) electricity production in CH of all photovoltaic plants (820 kWh/kWp) delivered to the grid. Dataset only applicable for the comparison of average energy technologies as also PV plants with a low performance are included in the statistics. For comparison of optimum installations the yield has to be corrected. A lifetime of 30 years is taken into account for the PV installation.	Annual output of grid-connected PV power plants differentiated for Roof-Top and Facade plants. Literature data for optimum installation and not real performance in the country have been corrected with a factor of 92% according to experiences in Switzerland for average production. Mix of PV-plants based on world wide average and own assumptions. A lifetime of 30 years is taken into account for the PV installation.	Annual output of grid-connected PV power plants differentiated for Roof-Top and Facade plants. Literature data for optimum installation and not real performance in the country have been corrected with a factor of 92% according to experiences in Switzerland for average production. Mix of PV-plants based on world wide average and own assumptions. A lifetime of 30 years is taken into account for the PV installation.	Annual output of grid-connected PV power plants differentiated for Roof-Top and Facade plants. Literature data for optimum installation and not real performance in the country have been corrected with a factor of 92% according to experiences in Switzerland for average production. Mix of PV-plants based on world wide average and own assumptions. A lifetime of 30 years is taken into account for the PV installation.	Annual output of grid-connected PV power plants differentiated for Roof-Top and Facade plants. Literature data for optimum installation and not real performance in the country have been corrected with a factor of 92% according to experiences in Switzerland for average production. Mix of PV-plants based on world wide average and own assumptions. A lifetime of 30 years is taken into account for the PV installation.
	Category	photovoltaic	photovoltaic	photovoltaic	photovoltaic	photovoltaic
	SubCategory	power plants	power plants	power plants	power plants	power plants
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	2000	2005	2005	2005	2005
	EndDate	2005	2006	2006	2006	2006
	OtherPeriodText	Calculation for yield based on average production in time period.	Time of publications	Time of publications	Time of publications	Time of publications
Geography	Text	Use in CH.				
Technology	Text	Electricity production with grid-connected photovoltaic power plants on buildings.	Electricity production with grid-connected photovoltaic power plants on buildings.	Electricity production with grid-connected photovoltaic power plants on buildings.	Electricity production with grid-connected photovoltaic power plants on buildings.	Electricity production with grid-connected photovoltaic power plants on buildings.
Representativene	Percent	100	100	100	100	100
	ProductionVolume	In 2005 there were 1900 PV-plants with an annual production of 17800MWh	not known	not known	not known	not known
	SamplingProcedure	Statistical data for CH.	Model calculations based on horizontal irradiation in the country.	Model calculations based on horizontal irradiation in the country.	Model calculations based on horizontal irradiation in the country.	Model calculations based on horizontal irradiation in the country.
	Extrapolations	none	Use of PV technology data investigated for Switzerland. No country specific investigation regarding current supply of PV installations. Correction of average yield	Use of PV technology data investigated for Switzerland. No country specific investigation regarding current supply of PV installations. Correction of average yield	Use of PV technology data investigated for Switzerland. No country specific investigation regarding current supply of PV installations. Correction of average yield	Use of PV technology data investigated for Switzerland. No country specific investigation regarding current supply of PV installations. Correction of average yield

13 Chemicals and pre-products

13.1 Fluorspar and hydrogen fluoride

13.1.1 Introduction

About 80% of the fluorspar (CaF_2) production world-wide is used for the production of hydrogen fluoride. This is a basic chemical component of most chemicals containing fluorine. The most important producers of CaF_2 are China (63%), South-Africa (26%) and Mexico (11%). The worldwide production in the year 2000 amounts to about 4.5 Million tonnes. The worldwide resources are estimated to be about 500 Million tonnes (Miller 2002).

13.1.2 Process description

Hydrogen fluoride is mainly produced from the decomposition of fluorspar with sulphuric acid according to the following reaction (<Ullmann 1985> and <EPA 1988>):

$$CaF_2 + H_2SO_4 \rightarrow CaSO_4\ (s) + 2\ HF$$

The main raw material is acid spar containing about 97% CaF_2. This is produced through flotation of grinded fluorspar. The endothermic reaction is taking place in a revolving oven that is heated from the outside. Waste gases are cleaned with sulphuric acid from dust and water. Then the hydrogen fluoride is condensed in a chain of coolers. With an after washing with concentrated sulphuric acid the remaining hydrogen fluoride is absorbed and recycled in the oven. The waste gases from the washer (mainly SiF_4) are purified in a hydrolisator <Ullmann 1985>:

$$3\ SiF_4 + 2\ H_2O \rightarrow 2\ H_2SiF_6 + SiO_2$$

Hexafluoride silica acid (H_2SiF_6) is fed to the further processing. The by-product calcium sulphate can be neutralized with lime, then it can be processes to synthetic anhydrite (gypsum) <Ullmann 1985>.

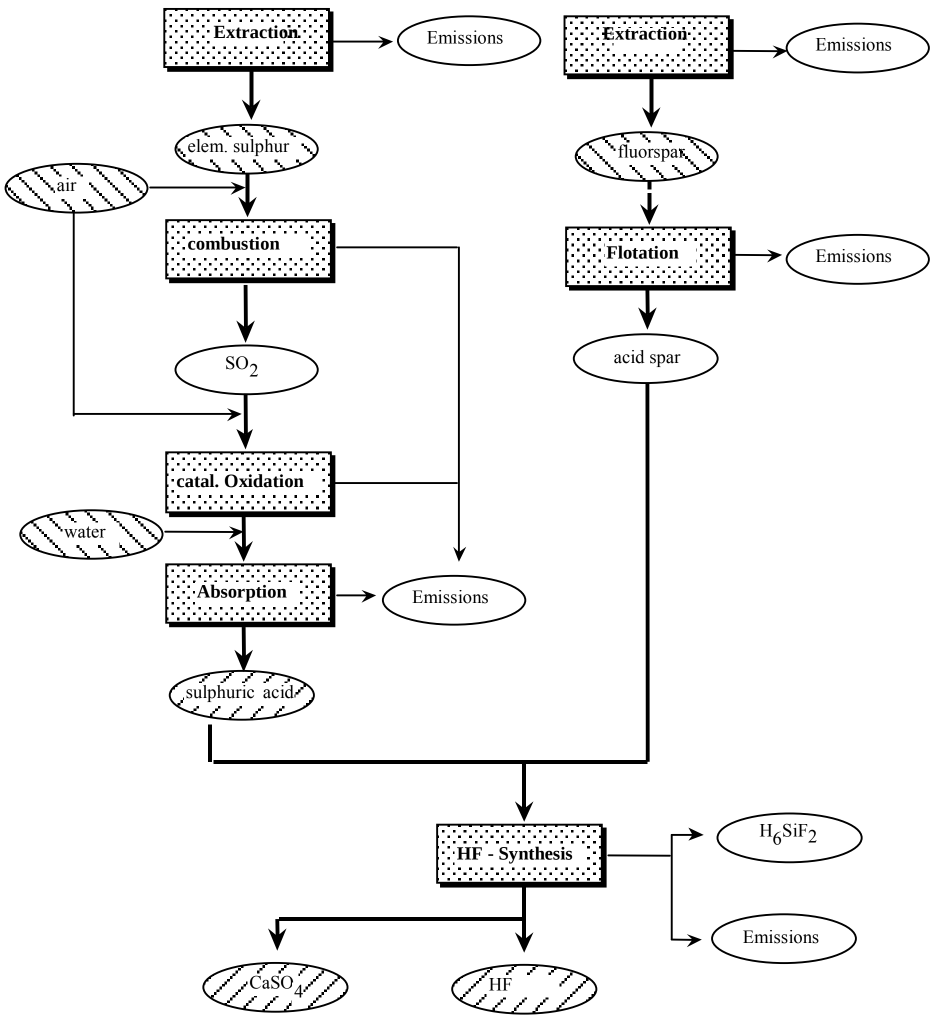

Fig. 13.1 Process stages for the production of hydrogen fluoride

13.1.3 Life cycle inventory

Fluorspar is produced in open-cast mining. The Vergenoeg Mining Company, South Africa, produces it in a mine with a size of approximately 1300 by 400 m^2. After three stages of grinding, the fluoride is separated by flotation. Further purification stages and a magnetic separation follow. Humidity is removed in a vacuum filter. The final product contains 97% CaF_2 (Metorexgroup 2002). Further information are derived from <Gruber et al. 1991>.

The amounts of the raw products fluorspar and sulphuric acid per kg of hydrogen fluoride have been investigated in (Krieger & Roekens-Guibert 2006).

Dust emissions due to fluorspar mining are reported by the US-EPA (1986) Further data for emissions were not available. The energy use for mining has been investigated by Boustead & Hancock (1979).

According to <Ullmann 1985> important resources of fluorspar are located in Upper Palatinate (Germany). A transport by truck is assumed to be 100 km for the extracted CaF_2.

Emissions for the hydrogen fluoride production are estimated based on literature <EPA 1988>. The reaction of CaF_2 with sulphuric acid is endothermic and uses about 1 MJ heat per kg hydrogen fluoride. A process specific energy use has been estimated roughly based on information provided in the literature (Krieger & Roekens-Guibert 2006, see Fig. 13.3). Tab. 13.1 shows the unit process raw data for fluorspar and hydrogen fluoride.

Tab. 13.1 Unit process raw data of fluorspar and hydrogen fluoride production (HF)

	Name	Location	InfrastructureProcess	Unit	fluorspar, 97%, at plant	hydrogen fluoride, at plant			
	Location				GLO	GLO			
	InfrastructureProcess				0	0			
	Unit				kg	kg			
resource, in ground	Fluorspar, 92%, in ground	-	-	kg	1.05E+0	-	1	1.33	(3,3,4,3,1,5); Estimation, 5% loss
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	6.22E-2	2.56E+0	1	1.60	(3,3,5,5,1,5); Boustead 1979
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	5.81E-1	-	1	1.60	(3,3,5,5,1,5); Boustead 1979
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	6.22E-2	1.12E+0	1	1.60	(3,3,5,5,1,5); Boustead 1979
	chemical plant, organics	RER	1	unit	4.00E-10	4.00E-10	1	3.90	(5,na,1,1,5,na); Rough estimation
	fluorspar, 97%, at plant	GLO	0	kg	-	2.05E+0	1	1.09	(2,3,1,2,1,na); Krieger 2006
	sulphuric acid, liquid, at plant	RER	0	kg	-	5.50E+0	1	1.09	(2,3,1,2,1,na); Krieger 2006
	transport, lorry >16t, fleet average	RER	0	tkm	-	7.55E-1	1	2.09	(4,5,na,na,na,na); CaF2: 100 km, standard dis
	transport, freight, rail	RER	0	tkm	-	3.30E+0	1	2.09	(4,5,na,na,na,na); standard distance 600km
emission air, unspecified	Heat, waste	-	-	MJ	2.24E-1	9.21E+0	1	1.60	(3,3,5,5,1,5); Calculation
	Hydrogen fluoride	-	-	kg	6.94E-5	-	1	2.34	(3,3,4,3,5,5); Estimation
	Particulates, < 2.5 um	-	-	kg	3.75E-5	-	1	3.98	(3,3,5,5,5,5); Literature
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.43E-4	-	1	2.96	(3,3,5,5,5,5); Literature
	Particulates, > 10 um	-	-	kg	1.95E-4	-	1	2.53	(3,3,5,5,5,5); Literature
	Sulfur dioxide	-	-	kg	-	3.00E-4	1	1.33	(3,3,4,3,1,5); HF production

13.2 Polyvinylfluoride films and pre-products (Tedlar® PVF Films)

13.2.1 Introduction[48]

Tedlar® PVF films are tough, durable, preformed polyvinyl fluoride films that are manufactured in continuous rolls. The unique weathering, mechanical, electrical, chemical, and stain-resistant properties of Tedlar® make it an ideal protective surfacing material for many applications as well as an ideal release film. Tedlar® PVF films can be oriented or non-oriented as in the Tedlar® Special (SP) film line. Film thickness can range from 12.5 microns (0.5 mil) to 50 microns (2 mil) and can be treated for adherability or left untreated for release applications.

13.2.2 Production process

Fig. 13.2 shows the process supply chain for Tedlar ® films produced by DuPont (Krieger & Roekens-Guibert 2006). Red and gold colours indicate process stages in DuPont facilities while grey boxes refer to purchased products. All following descriptions of individual pre-products and data are taken from the underlying publication (Krieger & Roekens-Guibert 2006) if not mentioned otherwise.

[48] Producers information on www.dupont.com.

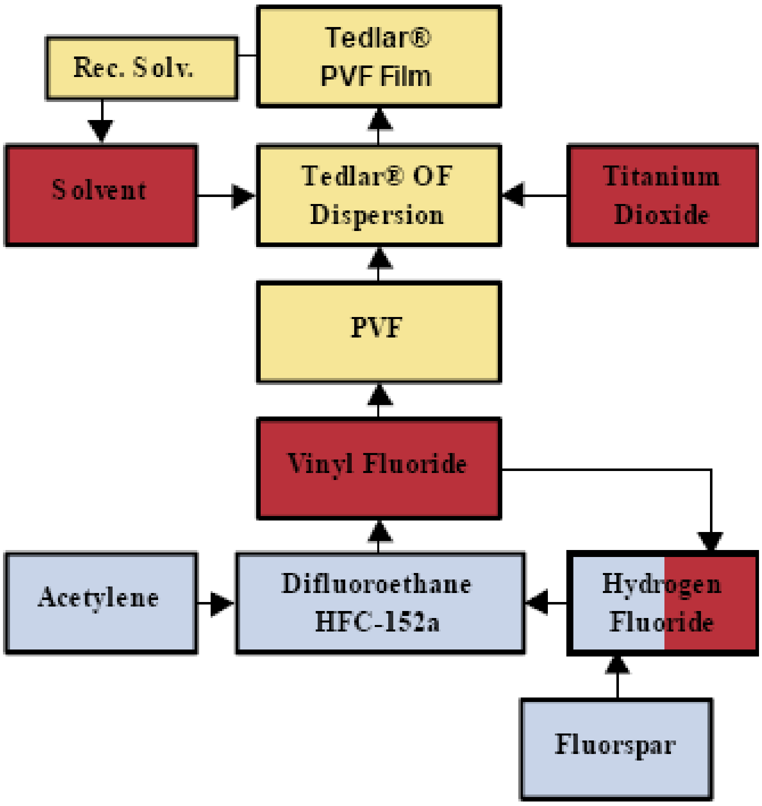

Fig. 13.2 Process supply chain for the production of PVF-films (Tedlar ®) (Krieger & Roekens-Guibert 2006)

13.2.3 1,1-difluoroethane, HFC-152a

A low pressure, liquid-phase, acetylene-based process was used to model the production of HFC-152a using a BF_3 catalyst (Krieger & Roekens-Guibert 2006).

$$H\text{-}C{\equiv}C\text{-}H + 2\ HF \rightarrow H_3C - CHF_2$$

The HF yield from the calculated input is assumed to be 95% while acetylene yield is estimated at 92.4%. The total process energy consumption at the HFC-152a facility is 4.9 MJ/kg HFC-152a, mostly from electricity (Krieger & Roekens-Guibert 2006, own assumption 80%). The catalyst and other raw materials (lime) contribute less than 1% to energy consumption. Further information, e.g. on emissions are not available.

13.2.4 Vinylfluoride

Vinyl fluoride (VF) production is modelled based on production at DuPont's Louisville, KY site. Difluoroethane (HFC-152a) is reacted to yield vinyl fluoride and hydrogen fluoride.

$$H_3C - CHF_2 \rightarrow H_2C = CH_2F + HF$$

The co-product HF is allocated by HF avoidance in the underlying publication. Thus a credit is given for the couple product HF produced in the process.[49] Transport of HFC-152a is estimated with stan-

[49] This is not fully in line with the general rules applied in ecoinvent data for allocation problems. In this case an allocation could not be made because of lack of data.

dard distances. The process energy requirements for the VF facility are 8.5 MJ per kg product, 75% steams from natural gas. The total process energy from cradle-to-gate for VF production (60.7 MJ/kg) is less than that for HFC-152a production due to the HF avoidance credit (Krieger & Roekens-Guibert 2006).

13.2.5 Polyvinylfluoride

Vinyl fluoride is polymerized by free-radical processes. The process requires high pressure (Carlsson & Schmiegel 2005). No further description of this stage is available in the underlying publication. Data for this stage have been desaggregated as described later.

13.2.6 Polyvinylfluoride, dispersion

The PVF polymer is mixed in a solvent with titanium dioxide and other minor additives to form a dispersion. The dispersion is coalesced into a melt in an extruder and formed into a web through a hopper die. The melt is quenched in a water/solvent bath, then stretched in both the machine direction and the transverse direction and dried in a tenter frame drying oven. Solvent is recovered from both the quench station and the dryer and recycled via distillation. The film is adhesion treated, slit to width, and packaged for shipment to a lamination facility. Some film is flaked and recycled to the dispersion to minimize yield loss (Krieger & Roekens-Guibert 2006).

13.2.7 PVF film production

No specific information on this process stage is available.

13.2.8 Solvent use

Acetic acid and Dimethylamine (DMA) are reacted without catalyst to form dimethylacetimde, DMAc. Emissions were estimated by assuming that the yield losses are released in the form of acetic acid, DMA, and DMAc. They are incinerated, releasing 0.15 kg CO_2 and 0.04 kg NO_x per kg DMAc produced. The input of solvent is modelled here with acetic acid (Krieger & Roekens-Guibert 2006).

13.2.9 Life cycle inventories of PVF-film production

A life cycle assessment for the production of PVF-films has been elaborated by Krieger & Roekens-Guibert (2006) whose results are shown in Fig. 13.3. However, only cumulative data are shown here. Due to confidentiality concerns the detailed inventory data were not available. The data from the above mentioned publication have been disaggregated in order to calculate about the same results as shown in the underlying publication. The unit process raw data for the single production stages are shown in Tab. 13.2. For all process steps the inputs of the main reactants are calculated with an efficiency of 95%. The data for the energy uses are based as far as possible on information in the paper. The emissions of HFC-152a are roughly assessed based on the published figure for the GWP in these process stages not resulting due to direct energy uses.

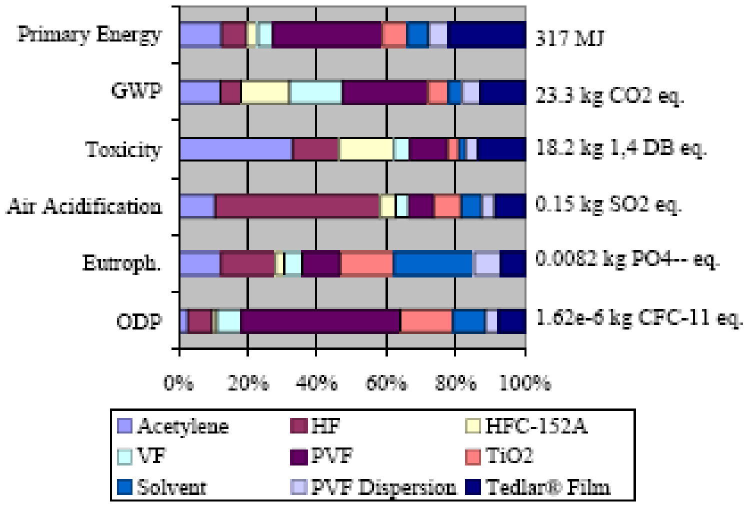

Fig. 13.3 **Environmental impacts of the production of 1 kg Tedlar ® films by process step (Krieger & Roekens-Guibert 2006)**

Tab. 13.2 **Unit process raw data of polyvinylfluoride films**

	Name	Location	InfrastructureProcess	Unit	1,1-difluoroethane, HFC-152a, at plant	vinylfluoride, at plant	polyvinylfluoride, at plant	polyvinylfluoride, dispersion, at plant	polyvinylfluoride film, at plant			
	Location				US	US	US	US	US			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
	electricity, medium voltage, at grid	US	0	kWh	1.09E+0	5.90E-1	4.76E+0	8.72E-1	2.81E+0	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	9.80E-1	6.38E+0	5.14E+1	9.42E+0	3.03E+1	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	chemical plant, organics	RER	1	unit	4.00E-10	4.00E-10	4.00E-10	4.00E-10	4.00E-10	1	3.27	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	hydrogen fluoride, at plant	GLO	0	kg	6.37E-1	-4.58E-1	-	-	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	1,1-difluoroethane, HFC-152a, at plant	US	0	kg	-	1.51E+0	-	-	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	vinylfluoride, at plant	US	0	kg	-	-	1.05E+0	-	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	polyvinylfluoride, at plant	US	0	kg	-	-	-	1.05E+0	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	polyvinylfluoride, dispersion, at plant	US	0	kg	-	-	-	-	8.04E-1	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	acetylene, at regional storehouse	CH	0	kg	4.27E-1	-	-	-	-	1	1.57	(5,3,1,1,1,5); Acetylen yield is 92.4%
	acetic acid, 98% in H2O, at plant	RER	0	kg	-	-	-	4.71E-1	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	dimethylamine, at plant	RER	0	kg	-	-	-	-	-	1	1.57	(5,3,1,1,1,5); Emitted, but amount not known
	titanium dioxide, production mix, at plant	RER	0	kg	-	-	-	-	2.48E-1	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	lime, hydrated, packed, at plant	CH	0	kg	2.14E-2	-	-	-	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	zinc, primary, at regional storage	RER	0	kg	1.97E-3	-	-	-	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	sulphuric acid, liquid, at plant	RER	0	kg	-	-	-	-	-	1	1.57	(5,3,1,1,1,5);
	transport, lorry >16t, fleet average	RER	0	tkm	1.09E-1	1.05E-1	1.05E-1	1.52E-1	1.05E-1	1	2.28	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	transport, freight, rail	RER	0	tkm	2.70E-1	9.08E-1	-	2.82E-1	1.49E-1	1	2.28	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	transport, transoceanic freight ship	OCE	0	tkm	6.37E+0	-	-	-	-	1	2.28	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
emission air, unspecified	Heat, waste	-	-	MJ	3.92E+0	2.13E+0	1.71E+1	3.14E+0	1.01E+1	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	Nitrogen oxides	-	-	kg	-	-	-	1.88E-2	-	1	1.83	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	Carbon dioxide, fossil	-	-	kg	-	-	-	7.06E-2	-	1	1.57	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006
	Ethane, 1,1-difluoro-, HFC-152a	-	-	kg	1.36E-2	2.05E-2	-	-	-	1	1.83	(5,3,1,1,1,5); Rough estimation based on cumulative data, Krieger et al. 2006

13.2.10 Crosscheck of results

The preliminary cumulative results based on ecoinvent data v1.3 have been crosschecked with the LCA software SimaPro with the published results shown in Fig. 13.3. In general the match is quite good. Only for toxicology it is not fully clear which indicator has been used in the paper and how the large difference can be explained.

Tab. 13.3 Cross check of preliminary cumulative results calculated with ecoinvent data v1.3 with the published data

Impact category	Unit	polyvinylfluoride film, at plant/kg/US	Krieger 2006
cumulative energy demand	MJ-Eq	314	317
abiotic depletion	kg Sb eq	0.14	n.d.
global warming (GWP100)	kg CO2 eq	24.27	23.30
ozone layer depletion (ODP)	kg CFC-11 eq	1.28E-06	1.62E-06
human toxicity	kg 1,4-DB eq	5.37	18.20
fresh water aquatic ecotox.	kg 1,4-DB eq	1.27	
marine aquatic ecotoxicity	kg 1,4-DB eq	1.25E+04	
terrestrial ecotoxicity	kg 1,4-DB eq	0.04	
photochemical oxidation	kg C2H4	6.02E-03	n.d.
acidification	kg SO2 eq	0.13	0.15
eutrophication	kg PO4--- eq	6.95E-03	8.20E-03

13.3 Meta information of PV fluorine chemicals

Tab. 13.4 show the EcoSpold meta information of fluorine chemicals investigated in this chapter.

Tab. 13.4 EcoSpold meta information of fluorine chemicals

ReferenceFunction	Name	fluorspar, 97%, at plant	hydrogen fluoride, at plant	1,1-difluoroethane, HFC-152a, at plant	vinylfluoride, at plant	polyvinylfluoride, at plant	polyvinylfluoride, dispersion, at plant	polyvinylfluoride film, at plant
Geography	Location	GLO	GLO	US	US	US	US	US
ReferenceFuncti	InfrastructureProcess	0	0	0	0	0	0	0
ReferenceFuncti	Unit	kg	kg	kg	kg	kg	kg	kg
	IncludedProcesses	Mineral extraction of calcium fluoride (fluorspar).	Production of hydrogen fluoride from fluorspar and sulphuric acid.	Pre-products, energy use, infrastructure, some air emissions and transports. No full information on all air and water emissions available.	Pre-products, energy use, infrastructure, some air emissions and transports. No full information on all air and water emissions available.	Pre-products, energy use, infrastructure, some air emissions and transports. No full information on all air and water emissions available.	Pre-products, energy use, infrastructure, some air emissions and transports. No full information on all air and water emissions available.	Pre-products, energy use, infrastructure, some air emissions and transports. No full information on all air and water emissions available.
	LocalName	Flussspat, 97%, ab Werk	Fluorwasserstoff, ab Werk	1,1-Difluorethan, HFC-152a, ab Werk	Vinylfluorid, ab Werk	Polyvinylfluorid, ab Werk	Polyvinylfluorid, Dispersion, ab Werk	Polyvinylfluorid-Folie, ab Werk
	Synonyms	calcium fluoride	Flusssäure	R152a//1,1-Difluoroethylene	Ethylene, fluoro-// Fluoroethene// Fluoroethylene// Monofluoroethylene// Vinyl fluoride//			Tedlar//Tefzel
	GeneralComment	Basic inventory based on old literature information.	Basic inventory based on own assumptions.	Basic inventory based on cumulative data.	Basic inventory based on cumulative data.	Basic inventory based on cumulative data.	Basic inventory based on cumulative data.	Basic inventory based on cumulative data.
	Category	chemicals	chemicals	chemicals	chemicals	chemicals	chemicals	chemicals
	SubCategory	inorganics	inorganics	organics	organics	organics	organics	organics
	Formula	CaF2	HF	C2H4F2	C2H3F	C2H3F	C2H3F	C2H3F
	StatisticalClassification							
	CASNumber	14542-23-5	73602-61-6	75-37-6	75-02-5	24981-14-4	24981-14-4	24981-14-4
TimePeriod	StartDate	1976	1979	2005	2005	2005	2005	2005
	EndDate	1991	2006	2006	2006	2006	2006	2006
	OtherPeriodText	Time of publications.	Time of publications.	Time of publications.	Time of publications.	Time of publications.	Time of publications.	Time of publications.
Geography	Text	Main producers are China, South Africa and Mexico. Some data for calcium fluoride produced in Germany.	Hydrogen fluoride is produced in different countries.	Production plant of DuPont in the United States.	Production plant of DuPont in the United States.	Production plant of DuPont in the United States.	Production plant of DuPont in the United States.	Production plant of DuPont in the United States.
Technology	Text	Open cast mining of resource. Separation by crushing, grinding and flotation.	Endothermic reaction of CaF2 and H2SO4.	Fluoropolymer chemistry.	Fluoropolymer chemistry.	Fluoropolymer chemistry.	Fluoropolymer chemistry.	Fluoropolymer chemistry.
Representativene	Percent	10	10	50	50	50	50	50
	ProductionVolume	A few million tonnes per year.	About 53'000 metric tonnes in the US.	Not known	Not known	Not known	Not known	Not known
	SamplingProcedure	Literature and own estimations.	Own estimations.	Publication of cumulative data.	Publication of cumulative data.	Publication of cumulative data.	Publication of cumulative data.	Publication of cumulative data.
	Extrapolations	none	Own assumptions for desaggregation of published cumulative data on energy use.	Desaggregation of published cumulative results for global warming potential and cumulative energy demand.	Desaggregation of published cumulative results for global warming potential and cumulative energy demand.	Desaggregation of published cumulative results for global warming potential and cumulative energy demand.	Desaggregation of published cumulative results for global warming potential and cumulative energy demand.	Desaggregation of published cumulative results for global warming potential and cumulative energy demand.

14 Summary of key parameters

14.1 Silicon use in the life cycle

One of the most important issues in LCA studies for PV is the material efficiency over all process stages. A range of different factors is important for this issue. Tab. 14.1 shows recent literature data for the use of purified silicon for solar cells. Most studies did not further describe the basic assumptions for these calculations.

Tab. 14.1 Literature data for the use of purified silicon for the production of crystalline PV cells

t/MWp (g/dm^2)	year	
17	2000	(Woditsch & Koch 2002)
17	2000	(Schmela 2002)
11-14 (14-18)	2000	(Scheer 2002)
15-20	2000	(Sarti & Einhaus 2002)
16	2000	(Räuber & Warmuth 2002)
11.5	2000	(Lauinger 2000)
12	2004	(Fawer 2006)
11	2005	(Fawer 2006)
11.5-12.5	2005	(Rogol 2005)
7	2010	forecast by Mr. Rogol, Photon-consulting.com

The material efficiency for silicon in the life cycle has been improved in the last years. The actual use of purified silicon has been calculated in the inventory according to Tab. 14.2 to 8, 9.6 and 6.8 kg per kW_p for sc-Si, mc-Si and ribbon-Si, respectively. The table shows also the data for the last version of the ecoinvent data v1.1 (Jungbluth 2003).

The silicon consumption has decreased considerably over the last few years, especially because of the current Si supply shortages. The silicon use for single-Si cells is indeed lower than for multi-Si. This is partly caused by the higher cell efficiency and because the wafer yields is higher (less breakage). Furthermore the cut-offs from the squaring process can be recycled very well.

These important figures have been verified with top-down data of the photovoltaics industry in Tab. 14.1. It is not clear how different authors considered the reuse of $SiCl_4$ and the recycling of silicon scraps. It is possible that internal recycling has not been considered in these calculations. The consumption has also declined considerably in the years 2004 to 2007. Thus, actual figures should be lower than shown in Tab. 14.1. The inventory for each stage seems to be quite reliable.

Tab. 14.2 Calculation of MG-silicon use in this study compared with ecoinvent data v1.1 (Jungbluth 2003)

	Unit	**single-Si 2003** unit	**multi-Si 2003** unit	**single-Si 2007** m2	**multi-Si 2007** m2	**ribbon-Si 2007** m2
yield, MG-Si to SoG-Si	%	95%	95%	*88%*	*88%*	*88%*
yield, SoG-Si to mc-/sc- silicon	%	*65%*	67%	*93%*	*88%*	*88%*
wafer thickness	µm	300	300	270	240	250
kerf loss (calculated for 2007 including other losses)	µm	200	200	191	249	-
wafer surface	cm^2	100	100	243	243	243
wafer weight	g	7.0	7.0	15	14	14
sawing losses, wafer	g	4.7	4.7	11	14	4
sawing losses, wafer	%	*40%*	*40%*	*41%*	*51%*	*21%*
out of this to recycling	%	*10%*	*10%*	*0%*	*0%*	*0%*
total silicon use for wafer	g	11.2	11.2	26	28	18
yield, wafer production	%	*63%*	*63%*	*59%*	*49%*	*79%*
yield, cell production	%	*95%*	*92%*	*94%*	*94%*	*94%*
purified silicon use per cell	g	18.1	18.2	30	34	22
purified silicon use per Wp	**g**	**11.0**	**12.3**	**8.0**	**9.6**	**6.8**
use MG-Si per cell	g	19.0	19.2	33.5	37.9	24.6
total yield, MG-Si to wafer	*%*	*36.8%*	*36.5%*	*45.7%*	*35.9%*	*57.6%*
MG-silicon per Wp	g	11.6	12.9	9.0	10.8	7.7
specific weight of silicon	g/cm3	2.33				

14.2 Changes in comparison to ecoinvent data v1.1 and older versions of the database

The full life cycle inventories and all assumptions are documented in the ecoinvent database. Tab. 14.3 shows the key parameters of the life cycle inventory. Main changes in comparison to older Swiss inventories are the update of the energy use in silicon purification, the location specific consideration of power consumption throughout the production chain, and the inclusion of many additional process specific emissions (Frischknecht et al. 1996; Jungbluth & Frischknecht 2000; Jungbluth 2003).

Tab. 14.3: Key parameters of the life cycle inventory for photovoltaic power production of sc-Si and mc-Si and comparison with previous Swiss studies (Frischknecht et al. 1996; Jungbluth & Frischknecht 2000; Jungbluth 2003)

	unit	**sc-Si**	**sc-Si**	**sc-Si**	**sc-Si**	**mc-Si**	**mc-Si**	**mc-Si**	**mc-Si**
	unit	1996	2000	2003	2007	1996	2000	2003	2007
MG-silicon production									
electricity use, NO (mainly hydro power)	kWh/kg		13.9	11	11		13.9	11	11
silicon purification (EG-Si or SoG-Si)									
electricity use, DE, plant specific	kWh/kg			103	44			103	44
electricity use, modified Siemens	kWh/kg				110				110
CZ-silicon production									
electricity use, UCTE-mix	kWh/kg		100	123	86			-	-
sc-Si and mc-Si wafer									
thickness, wafer	µm	300	300	300	270	300	300	300	240
sawing gap	µm	200	200	200	191	200	200	200	249
wafer area	cm^2	98	98	100	243	107	107	100	243
weight	g	7.11	6.85	6.99	15	7.76	7.48	6.99	14
cell power	Wp	1.62	1.62	1.65	3.73	1.5	1.5	1.48	3.50
cell efficiency	%	16.5%	15.8%	16.5%	15.3%	14.0%	13.4%	14.8%	14.4%
use of MG-silicon	g/Wafer	66.7	17.6	19.0	33.5	129.4	17.3	19.2	37.9
EG-silicon use per wafer	g/Wafer	12.2	12.7	11.2	26.2	23.8	13.8	11.2	27.7
electricity use	kWh/Wafe	1.57	1.4	0.3	0.19	1.56	1.6	0.3	0.19
sc-Si and mc-Si cells									
electricity use	kWh/cell	1.3	0.27	0.2	0.74	1.28	0.27	0.2	0.74
panel/ laminate, sc-Si/ mc-Si									
number of cells	cells/pane	36	36	112.5	37.6	36	36	112.5	37.6
panel area	cm^2	4290	4290	12529	10000	4400	4400	12529	10000
active area	cm^2	3528	3528	11250	9141	3856	3856	11250	9141
panel power	Wp	58	55.5	185	140	54	51.7	166	132
efficiency production	%	99%	99%	97%	98%	99%	99%	97%	98%
use of cells sc-Si/ mc-Si	cells/kW_p	627	649	608	268	673.4	696	677	285
process energy use	MJ/kW_p	0.75	0.75	0.23	0.16	3.23	0.75	0.26	0.17
3kWp-plant									
panel area	m^2/3kW_p	22.2	27.8	18.2	19.6	24.4	24.4	20.3	20.8
operation									
yield, slope-roof + flat roof	kWh/kW_p	860	886	885	922	860	886	885	922
yield, facade	kWh/kW_p	860		626	620	860		626	620
yield, CH PV electricity mix	kWh/kW_p	860		819	820	860		819	820

sc-Si = singlecrystalline silicon, mc-Si = multicrystalline silicon.

15 Cumulative results and interpretation

15.1 Introduction

Selected LCI results and values for the cumulative energy demand of the photovoltaic ecoinvent data v2.1 are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows showing by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in the 3rd ecoinvent report (Frischknecht et al. 2007b). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

15.2 Silicon production

Here we show the results for different qualities of silicon and purified silicon products (Tab. 15.1). The higher the demand for purity the higher are the environmental impacts caused. The solar-grade silicon reduces the results considerable compared to electronic-grade silicon used some years ago as a basic product for photovoltaics.

Tab. 15.1 Selected LCI results and the cumulative energy demand of purified silicon products

	Name		MG-silicon, at plant	silicon, solar grade, modified Siemens process, at plant	silicon, electronic grade, off-grade, at plant	silicon, electronic grade, at plant	silicon, production mix, photovoltaics, at plant	silicon, multi-Si, casted, at plant	CZ single crystalline silicon, electronics, at plant	CZ single crystalline silicon, photovoltaics, at plant
	Location		NO	RER	DE	DE	GLO	RER	RER	RER
	Unit	Unit	kg	kg	kg	kg	kg	kg	kg	kg
	Infrastructure		0	0	0	0	0	0	0	0
LCIA results										
cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	68.6	614.7	415.2	1'346.5	710.8	942.9	3'593.7	1'447.6
cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	8.0	22.9	12.7	23.6	22.5	109.4	909.5	408.8
cumulative energy demand	non-renewable energy resources, primary forest	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
cumulative energy demand	renewable energy resources, biomass	MJ-Eq	25.7	29.8	27.3	27.9	29.4	36.4	69.3	44.5
cumulative energy demand	renewable energy resources, solar, converted	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1
cumulative energy demand	renewable energy resources, potential (in barrage water), converted	MJ-Eq	38.8	292.6	81.4	192.7	267.0	314.0	374.8	329.5
cumulative energy demand	renewable energy resources, kinetic (in wind), converted	MJ-Eq	0.4	0.7	0.5	0.7	0.7	2.3	17.2	7.8
selected LCI results										
land occupation	resource	m2a	1.5E+0	2.1E+0	1.6E+0	1.9E+0	2.0E+0	2.5E+0	4.8E+0	3.2E+0
CO2, fossil	air	kg	4.5E+0	3.5E+1	2.3E+1	7.4E+1	4.0E+1	5.5E+1	2.3E+2	9.4E+1
NMVOC	air	kg	3.2E-3	1.9E-2	1.3E-2	4.0E-2	2.2E-2	2.7E-2	8.8E-2	3.7E-2
nitrogen oxides	air	kg	1.4E-2	7.8E-2	5.4E-2	1.6E-1	8.8E-2	1.2E-1	4.2E-1	1.8E-1
sulphur dioxide	air	kg	1.7E-2	3.7E-2	2.7E-2	5.0E-2	3.8E-2	7.7E-2	4.3E-1	2.0E-1
particulates, < 2.5 um	air	kg	9.6E-4	2.4E-3	1.5E-3	2.7E-3	2.4E-3	8.4E-3	3.4E-2	1.8E-2
BOD	water	kg	9.5E-3	1.6E-2	1.3E-2	1.9E-2	1.7E-2	2.4E-2	2.6E-1	2.3E-1
cadmium	soil	kg	3.8E-9	7.3E-9	5.2E-9	7.0E-9	7.1E-9	1.3E-8	5.7E-8	2.9E-8

15.3 Wafer and cell production

Tab. 15.2 shows selected results and the cumulative energy demand for wafer and cell production. The environmental burdens are quite dependent on the type of silicon input used.

Tab. 15.2 Selected LCI results and the cumulative energy demand of wafer and cell production per m^2 of wafer

	Name		multi-Si wafer, ribbon, at plant	photovoltaic cell, ribbon-Si, at plant	multi-Si wafer, at plant	photovoltaic cell, multi-Si, at plant	single-Si wafer, photovoltaics, at plant	photovoltaic cell, single-Si, at plant	single-Si wafer, electronics, at plant
	Location		RER	RER	RER	RER	RER	RER	RER
	Unit	Unit	m2	m2	m2	m2	m2	m2	m2
	Infrastructure		0	0	0	0	0	0	0
LCIA results									
cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	853	1'170	1'359	1'693	1'839	2'203	4'312
cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	213	373	212	370	527	703	1'164
cumulative energy demand	non-renewable energy resources, primary forest	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
cumulative energy demand	renewable energy resources, biomass	MJ-Eq	36	43	53	61	59	68	89
cumulative energy demand	renewable energy resources, solar, converted	MJ-Eq	0.1	0.1	0.1	0.1	0.1	0.2	0.3
cumulative energy demand	renewable energy resources, potential (in barrage water), converted	MJ-Eq	220	256	370	411	366	407	426
cumulative energy demand	renewable energy resources, kinetic (in wind), converted	MJ-Eq	4	7	4	7	10	13	22
selected LCI results									
land occupation	resource	m2a	2.8E+0	3.5E+0	4.2E+0	4.9E+0	4.7E+0	5.5E+0	6.8E+0
CO2, fossil	air	kg	5.3E+1	7.7E+1	8.1E+1	1.0E+2	1.2E+2	1.4E+2	2.8E+2
NMVOC	air	kg	2.3E-2	2.2E-1	4.1E-2	2.4E-1	5.0E-2	2.5E-1	1.1E-1
nitrogen oxides	air	kg	1.1E-1	1.6E-1	1.7E-1	2.2E-1	2.3E-1	2.9E-1	8.9E-1
sulphur dioxide	air	kg	1.1E-1	1.9E-1	1.4E-1	2.3E-1	2.7E-1	3.6E-1	5.6E-1
particulates, < 2.5 um	air	kg	8.2E-3	1.7E-2	1.5E-2	2.5E-2	2.5E-2	3.5E-2	4.6E-2
BOD	water	kg	5.3E-2	9.3E-2	2.3E-1	2.8E-1	4.5E-1	5.1E-1	6.4E-1
cadmium	soil	kg	1.6E-8	2.6E-8	2.2E-8	3.1E-8	3.8E-8	4.8E-8	7.4E-8

15.4 Solar panels and laminates

Tab. 15.3 shows selected results and the cumulative energy demand for different types of solar panels and laminates. Solar panels made with multicrystalline cell show the highest results per m^2 of panel surface. The results for thin film technologies are considerable lower. Laminates show lower results because frames are not used.

Tab. 15.3 Selected LCI results and the cumulative energy demand of solar panels per m^2

	Name		photovoltaic panel, ribbon-Si, at plant	photovoltaic panel, multi-Si, at plant	photovoltaic panel, single-Si, at plant	photovoltaic panel, a-Si, at plant	photovoltaic laminate, CdTe, at plant	photovoltaic laminate, CdTe, at plant	photovoltaic laminate, CdTe, mix, at regional storage	photovoltaic panel, CIS, at plant
	Location		RER	RER	RER	US	US	DE	RER	DE
	Unit	Unit	m2	m2	m2	m2	m2	m2	m2	m2
	Infrastructure		1	1	1	1	1	1	1	1
LCIA results										
cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1'623	2'111	2'586	861	976	884	954	1'423
cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	444	440	751	240	238	249	245	500
cumulative energy demand	non-renewable energy resources, primary forest	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
cumulative energy demand	renewable energy resources, biomass	MJ-Eq	65	82	88	19	30	31	30	31
cumulative energy demand	renewable energy resources, solar, converted	MJ-Eq	0.1	0.1	0.2	0.0	0.0	0.2	0.1	0.5
cumulative energy demand	renewable energy resources, potential (in barrage water), converted	MJ-Eq	279	424	421	63	28	22	26	53
cumulative energy demand	renewable energy resources, kinetic (in wind), converted	MJ-Eq	8	8	14	2	2	11	5	22
selected LCI results										
land occupation	resource	m2a	7.7E+0	8.9E+0	9.5E+0	2.5E+0	5.8E+0	5.5E+0	5.7E+0	3.5E+0
CO2, fossil	air	kg	1.1E+2	1.4E+2	1.7E+2	6.1E+1	7.5E+1	6.9E+1	7.4E+1	1.1E+2
NMVOC	air	kg	2.4E-1	2.5E-1	2.6E-1	3.1E-2	2.9E-2	2.6E-2	2.9E-2	3.2E-2
nitrogen oxides	air	kg	2.6E-1	3.2E-1	3.8E-1	1.3E-1	2.4E-1	1.8E-1	2.3E-1	2.0E-1
sulphur dioxide	air	kg	3.3E-1	3.6E-1	4.9E-1	2.9E-1	4.3E-1	2.3E-1	3.6E-1	2.2E-1
particulates, < 2.5 um	air	kg	2.8E-2	3.5E-2	4.4E-2	1.6E-2	1.8E-2	1.8E-2	1.8E-2	1.9E-2
BOD	water	kg	1.5E-1	3.2E-1	5.4E-1	4.9E-2	7.5E-2	6.9E-2	7.6E-2	8.3E-2
cadmium	soil	kg	4.7E-8	5.2E-8	6.8E-8	4.0E-7	2.1E-6	2.1E-6	2.1E-6	6.8E-8

15.5 Electricity production

Tab. 15.4 shows selected results and the cumulative energy demand for the electricity production with different types of 3kW$_p$ plants in Switzerland. It has to be noted that the ranking between different technologies changes compared to the comparison per m^2 of panel surface. This is due to the different efficiencies of the solar cells and thus quite different amounts of panels necessary per kWh produced. CO_2 emissions are in the range of 40-70 gram per kWh of electricity produced if the plants are operated in Switzerland.

Tab. 15.4 Selected LCI results and the cumulative energy demand of electricity production with 3kW$_p$ PV plants operated in Switzerland

	Name		electricity, PV, at 3kWp slanted-roof, single-Si, laminated, integrated	electricity, PV, at 3kWp slanted-roof, single-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, multi-Si, laminated, integrated	electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, ribbon-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, ribbon-Si, lam., integrated	electricity, PV, at 3kWp slanted-roof, a-Si, panel, mounted	electricity, PV, at 3kWp slanted-roof, a-Si, lam., integrated	electricity, PV, at 3kWp slanted-roof, CdTe, laminated, integrated	electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted
	Location		CH	CH	CH	CH	CH	CH	CH	CH	CH	CH
	Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
	Infrastructure		0	0	0	0	0	0	0	0	0	0
LCIA results												
cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.87	0.91	0.78	0.82	0.74	0.70	0.85	0.70	0.68	0.76
cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.25	0.26	0.17	0.19	0.20	0.19	0.23	0.19	0.17	0.24
cumulative energy demand	non-renewable energy resources, primary forest	MJ-Eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.01	0.02	0.02
cumulative energy demand	renewable energy resources, solar, converted	MJ-Eq	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
cumulative energy demand	renewable energy resources, potential (in barrage water), converted	MJ-Eq	0.13	0.14	0.14	0.15	0.12	0.10	0.09	0.06	0.05	0.06
cumulative energy demand	renewable energy resources, kinetic (in wind), converted	MJ-Eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
selected LCI results												
land occupation	resource	m2a	3.3E-3	3.4E-3	3.3E-3	3.5E-3	3.4E-3	3.2E-3	2.8E-3	2.2E-3	3.4E-3	2.3E-3
CO2, fossil	air	kg	5.9E-2	6.2E-2	5.2E-2	5.5E-2	5.1E-2	4.8E-2	6.1E-2	5.0E-2	5.1E-2	5.8E-2
NMVOC	air	kg	8.9E-5	9.0E-5	9.2E-5	9.3E-5	9.4E-5	9.4E-5	4.3E-5	3.9E-5	3.7E-5	3.4E-5
nitrogen oxides	air	kg	1.4E-4	1.4E-4	1.3E-4	1.4E-4	1.3E-4	1.2E-4	1.4E-4	1.1E-4	1.5E-4	1.2E-4
sulphur dioxide	air	kg	2.0E-4	2.2E-4	1.8E-4	1.9E-4	1.9E-4	1.8E-4	2.9E-4	2.4E-4	2.4E-4	1.7E-4
particulates, < 2.5 um	air	kg	2.0E-5	2.2E-5	1.8E-5	2.0E-5	2.0E-5	1.7E-5	2.4E-5	1.7E-5	1.9E-5	1.8E-5
BOD	water	kg	1.8E-4	1.9E-4	1.3E-4	1.4E-4	9.3E-5	8.7E-5	9.1E-5	7.4E-5	8.5E-5	7.8E-5
cadmium	soil	kg	8.0E-11	8.1E-11	7.7E-11	7.8E-11	7.8E-11	7.7E-11	2.9E-10	2.9E-10	9.4E-10	8.8E-11

Tab. 15.5 shows selected results and the cumulative energy demand for photovoltaic power plants in different countries. The comparison shows that there might be considerable differences between different countries depending on the irradiation and thus on the actual yield per kW$_p$ installed.

Tab. 15.5 Selected LCI results and the cumulative energy demand of electricity production with photovoltaic power plants in selected countries

	Name		electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant	electricity, production mix photovoltaic, at plant
	Location		CH	DE	ES	IT	JP	SE	US
	Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh
	Infrastructure		0	0	0	0	0	0	0
LCIA results									
cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.97	1.11	0.65	0.88	0.95	1.03	0.61
cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.25	0.28	0.17	0.22	0.24	0.26	0.15
cumulative energy demand	non-renewable energy resources, primary forest	MJ-Eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.03	0.03	0.02	0.03	0.03	0.03	0.02
cumulative energy demand	renewable energy resources, solar, converted	MJ-Eq	3.85	3.85	3.85	3.85	3.85	3.85	3.85
cumulative energy demand	renewable energy resources, potential (in barrage water), converted	MJ-Eq	0.16	0.18	0.11	0.15	0.16	0.17	0.10
cumulative energy demand	renewable energy resources, kinetic (in wind), converted	MJ-Eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
selected LCI results									
land occupation	resource	m2a	3.8E-3	4.4E-3	2.6E-3	3.5E-3	3.8E-3	4.1E-3	2.4E-3
CO2, fossil	air	kg	6.5E-2	7.5E-2	4.4E-2	5.9E-2	6.4E-2	7.0E-2	4.1E-2
NMVOC	air	kg	1.0E-4	1.2E-4	6.8E-5	9.2E-5	9.9E-5	1.1E-4	6.3E-5
nitrogen oxides	air	kg	1.6E-4	1.8E-4	1.1E-4	1.4E-4	1.5E-4	1.7E-4	9.9E-5
sulphur dioxide	air	kg	2.3E-4	2.7E-4	1.6E-4	2.1E-4	2.3E-4	2.5E-4	1.5E-4
particulates, < 2.5 um	air	kg	2.4E-5	2.7E-5	1.6E-5	2.2E-5	2.3E-5	2.5E-5	1.5E-5
BOD	water	kg	1.7E-4	2.0E-4	1.2E-4	1.6E-4	1.7E-4	1.8E-4	1.1E-4
cadmium	soil	kg	1.1E-10	1.3E-10	7.7E-11	1.0E-10	1.1E-10	1.2E-10	7.1E-11

15.6 Selected results for process stages

Here we make an evaluation of elementary flows over the life cycle.[50] Therefore emissions and resource uses are added up for all stages in the life cycle. Results are presented for one kWh of electricity. Fig. 15.1 shows the shares of different production stages for some selected elementary flows of a

[50] Elementary flows describe the input of resources (e.g. crude oil) and emissions to nature (e.g. carbon dioxide). About 1000 different elementary flows are recorded in the ecoinvent data v2.0.

slanted-roof installation with a multicrystalline silicon panel. As an example BOD (Biological Oxygen Demand) is emitted in high share due to the finishing of wafer surfaces. The analysis shows that each production stage might be important for certain elementary flows.

Compared to earlier investigations of PV, now the inverter and mounting systems get more importance. For most indicators these so called balance of system (BOS) elements have a share of 30% to 50%. This is due to the improvements, which could be observed for the production chain until the photovoltaic cell and the more detailed investigation of these additional elements, which for example includes now also electronic components of the inverter.

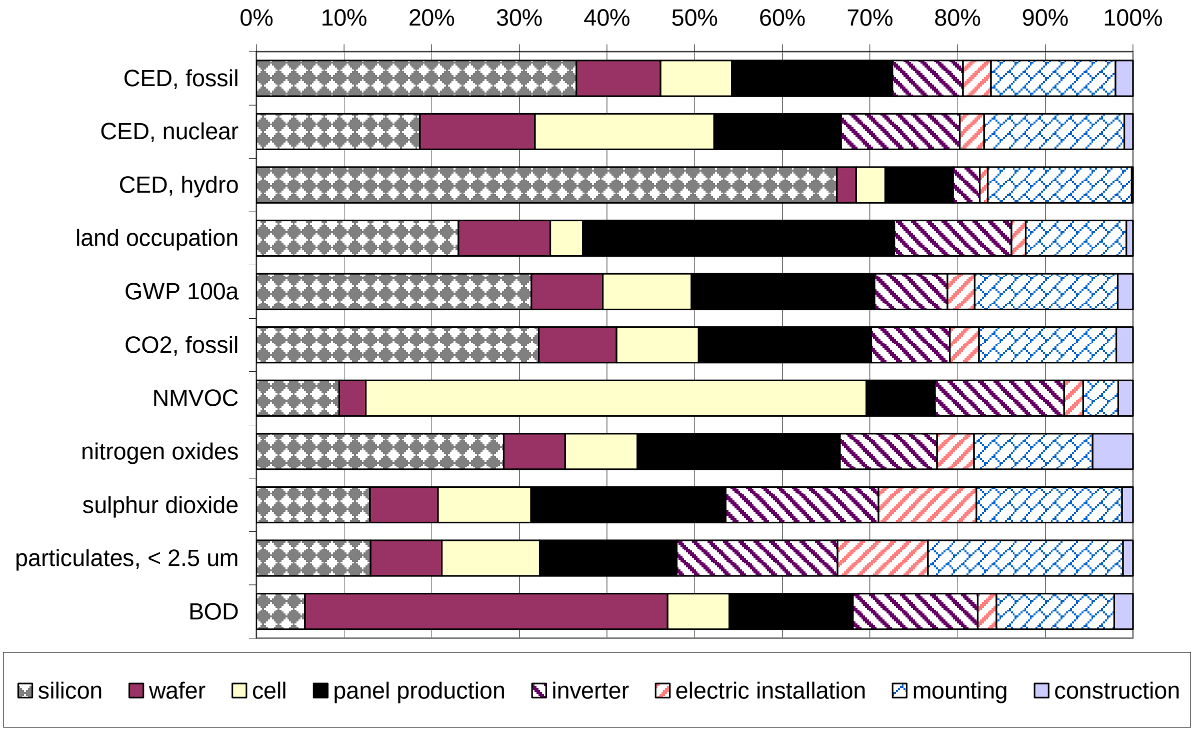

Fig. 15.1: Share of process stages for a Swiss grid-connected, 3kWp slanted-roof installation with a multicrystalline silicon panel for selected elementary flows of the inventory

15.7 Pay-back time

An important yardstick for the assessment of renewable energy systems is the estimation of the energy and/or environmental pay back time. In some publications the energy pay back time was defined as the time until the electricity production of the plant equals the energy use for the production of the plant. This does not take into account differences in the type of energy (e.g. nuclear or fossil resources) nor differences for the quality (e.g. electricity or heat use). Here we describe the time until environmental impacts from the production of the plant have been levelled out due to avoiding resource use and/or emissions of a conventional reference system that produces the same amount of electricity.

The outcome of such a comparison is influenced by the choice of the reference system on the one hand and the indicator on the other. Here we consider the UCTE electricity mix in year 2004 as the reference system. Fig. 15.2 shows the pay-back-time for the non-renewable cumulative energy demand for PV power plants operated in Switzerland. This time is between 2.5 and 4.9 years for the different types of PV plants. Thus, it is 5 to 10 times shorter than the expected lifetime of the photovoltaic power plants. Different factors like type of installation, type of cells, type of panel or laminates, etc. are important for such calculations.

The picture would change if other reference systems would be taken into account. These examples show that it is necessary to discuss the assumptions for a “pay back time” in detail and that the results of such an analysis are quite dependent on these assumptions.

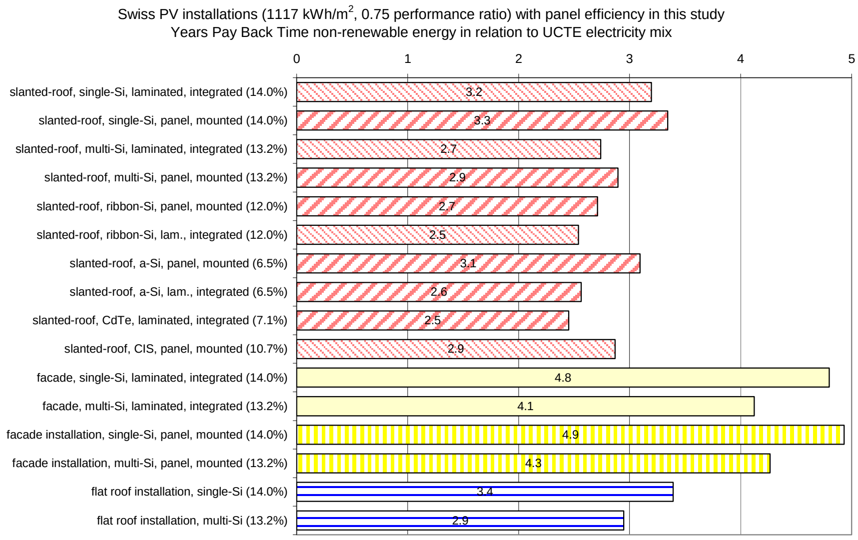

Fig. 15.2: Energy pay back time of 3 kWp photovoltaic power plants operated in Switzerland in relation to the UCTE electricity mix. red – slanted roof, yellow – façade, blue – flat roof

15.8 Changes in comparison to ecoinvent data v1.1 and older versions of the database

Fig. 15.3 shows the development of results for the cumulative energy demand of photovoltaic electricity in this study and in previous Swiss studies. The figure shows also the increase in installed capacity in Switzerland as reported in Fig. 2.1. This evaluation shows that the cumulative energy demand has been decreased by a factor of 3 or more since the first studies on PV systems made in the early nineties.

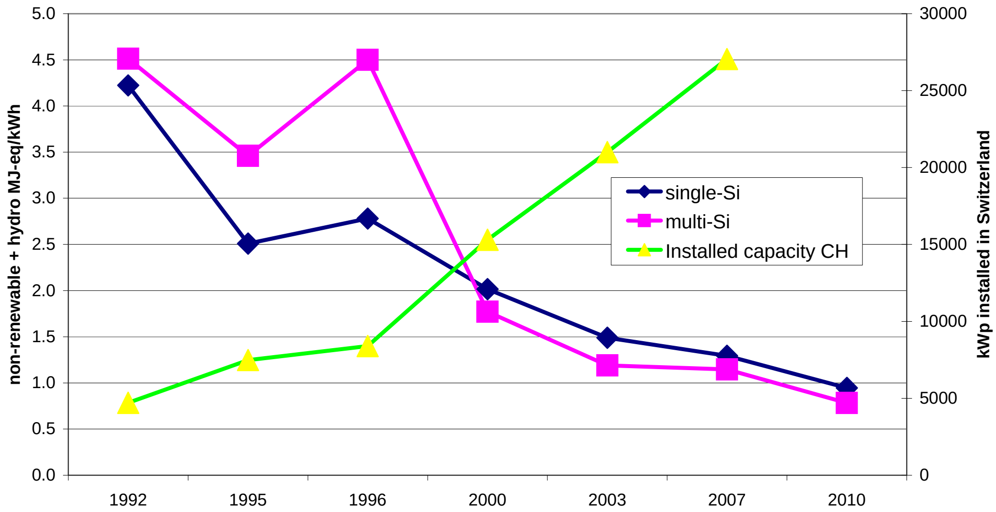

Fig. 15.3 Cumulative energy demand of the life cycle inventory for Swiss photovoltaic power production in this study (2005) and comparison with previous Swiss studies. Data for 2010 are forecasted in 2003 (Frischknecht et al. 1994; Frischknecht et al. 1996; Jungbluth & Frischknecht 2000; Jungbluth 2003)

16 Conclusion and Outlook

16.1 Conclusion

The life cycle inventories of photovoltaic power plants can be assumed to be representative for photovoltaic plants and for the average photovoltaic mix in Switzerland and in other European countries operated in the year 2005. The average electricity mix in Switzerland considers the actual performance of the installed plants, while plant data (e.g. laminate and panel, single- or multicrystalline) can be used for comparisons of different technologies. The yield data for PV electricity mixes in other countries are based on assumptions for optimum installations and a correction factor which takes into account an actually lower yield of installations in Switzerland. The analysis of the results shows that it is quite important to take the real market situation (raw material supply, electricity, etc.) into account.

Differences for the situation in other European countries in comparison to the data modelled for Switzerland are mainly due to different solar irradiation. It should be considered that the inventory may not be valid for wafers and panels produced outside of Europe or US, because production technologies and power mix for production processes are generally not the same. The datasets on PV electricity in non-European countries should thus be revised as soon as data are available for production patterns in more producing countries e.g. Japan.

For the modelling of a specific power plant or of power plant mixes not addressed in this report it is advisable to consider at least the annual yield (kWh/kW_p) and if possible also the actual size of the plant in square metres. Furthermore it is necessary to clearly define if average, plant-specific or optimum performance ratios are taken into account.

The analysis in this report is focus on the today production patterns and operation results. For the comparison of energy technologies it is advisable to take into account also future development potentials. Several studies are available for PV technologies which take into account also possible future improvements in the production chain.

The type of electricity used in different production stages might be quite important for the caused environmental impacts. If a specific situation different from what assumed in the present study is investigated, the specific sources of electricity supply should be considered. Some PV producers also use photovoltaic electricity for their own production process.[51] This has not been considered in the modelling of this study.

The analysis of the environmental impacts with different LCIA methods shows that it is quite important to include process specific emissions of the production chain. Many, but not all possible emissions are investigated in this study. It is necessary to evaluate all types of environmental impacts with different LCIA methodologies if photovoltaic power plants shall be compared with other energy systems.

Compared to earlier investigations of PV, today the inverter and mounting systems get more and more importance. For most indicators these so called balance of system (BOS) elements have a share of 30% to 50%. On the one side, this is due to the improvements, which could be observed for the production chain until the photovoltaic cell. On the other side we now have a more detailed investigation of these additional elements, which for example includes now also electronic components of the inverter.

16.2 Recommendations for future updates

The whole production chain for photovoltaics is subject to rapid changes. An example is the supply

[51] The solar cell manufacturing plant in Gelsenkirchen produces a part of the own electricity consumption with solar cells installed on the factory roof.

situation for the silicon feedstock, which totally changed during the last four years.

Some emission data in the inventory are based only on single information source, some are from one specific producer only. Thus they should be verified with data from other production companies and factories to the extent possible. In cases where several information sources were available they showed partly a large variation. A general problem is that data had to be mixed from different sources with possibly different assumptions and boundaries.

The projected lifetime is a key parameter for the assessment, but operational experience with the new technologies is not yet sufficient to derive reliable conclusions. The degradation in a-Si may limit the lifetime of this specific type of power plants. Many production processes, especially for photovoltaic power, are still under development. Thus, future updates of the LCI should verify key assumptions on energy and material uses as well as emissions, which are important for the LCIA. The allocation procedure applied for the silicon purification process is dependent on the actual market conditions and therefore needs to be revised if these conditions change.

The ecoinvent database provides detailed background data for a range of materials and services used in the production chain of photovoltaics. These data can also be used to assess the environmental impacts for the production of photovoltaic power plants in other countries or to investigate other technologies.

Some specific recommendations follow.

16.2.1 New solar grade silicon processes (new SoG-silicon)

It is expected that solar grade silicon from new process routes will enter the market quite soon. These process routes should be investigated as soon as reliable data are available.

16.2.2 Balance of system for large PV-power plants

The unit process raw data for the mounting systems are based on recent information about the weights of such installations manly used in Switzerland. Such data show a large variation and also some regional influence due to e.g. different weather conditions. It would be recommended to update again these data with the next revision of this report. Therefore it should be considered that most of the PV plants installed today on buildings or open-ground have a capacity of more than 3 kW_p. Most of the installed capacity today is in plants with 10 to 100 kW_p. Thus, for the next version also plants with a capacity of about 20-50 kW_p should be investigated.

In some countries ground-mounted, south-facing latitude-tilt installations are the fastest growing section of PV. It should be considered to investigate also such open-ground installations even if they are so far not so relevant in the case of Switzerland.

16.2.3 Further PV technologies

Further thin film technologies should be investigated in a mid-term time frame. Updated data might be available from an ongoing European project.[52]

InGaP and InGaP/sc-Si solar

At the moment, the InGaP technology is yet not very important. Two publications (Meijer et al. 2003; Mohr et al. 2007) contain some detailed data. However, we currently consider it too premature to start

[52] EU-Projekt ATHLET (www.ip-athlet.eu)

fully LCA investigations on this technology.

Flexible cells

A life cycle assessment for a-Si on flexible substrate has been elaborated by a Swiss company (Teuscher & Jianghong 2007). It investigates the production with first experiences from commercial production. This is planned to be updated in the moment and might be available for the next version of ecoinvent data.

Other new technologies

There are several other new thin film technologies such as:

- Dye sensitized solar cells (First LCA studies by Greijer et al. 2001; Veltkamp & de Wild-Scholten 2006)
- Polymercells (First LCA studies by Löfgren & Zettergren 2006)
- CSG (Thalheim). In the CSG production process, silicon is not required in the form of silicon wafers but comes from silane gas. A very thin layer of silicon, less than two microns thick, is deposited directly onto the textured surface of a glass sheet that traps light in the thin silicon. The silicon is crystallised by heating. The resulting layer is processed using patented laser and ink-jet printing techniques to form the electrical contacts.[53]
- Concentrator photovoltaics (First LCA studies by Kim & Fthenakis 2006; Löfgren & Zettergren 2006)

So far they are only produced in small amounts in pilot plants. It was not be possible to investigate them for ecoinvent data v2.1. The development will be observed in the next years. Data should be included in the ecoinvent database as soon as commercial production has started and reliable data are available.

16.2.4 Missing chemicals inventories

The following chemicals, used in the production of photovoltaics, are so far not investigated for the ecoinvent database. It is recommended to include them for future extensions of the database (see also de Wild-Scholten et al. 2007):

- CF_4 perfluoromethane
- C_2F_6 perfluoroethane
- NF_3 nitrogen trifluoride

16.2.5 Actual performance data for electricity mixes outside Switzerland

It would be advisable to consider actual performance data instead of yields for optimum installations for the calculation of all PV electricity mixes if such data would be available.

16.2.6 Production patterns in Asia and North-America

For the electricity production outside Europe it would be recommended to investigate the production

[53] http://www.csgsolar.com

patterns for PV technologies also for Asia and North-America.

16.2.7 End of life treatment

So far no sufficient data exist for the end of life treatment of photovoltaic panels. It can be expected that take back systems as for electronics must and will be erased for photovoltaics because of legislation. Such systems are already planned (Müller et al. 2004; Warmbach et al. 2004). The environmental impacts caused by dismantling, transport to recycling plant and further treatment should be investigated as soon as reliable data are available. Such take back systems might further improve the results of the life cycle assessment of PV plants.

Glossary and abbreviations

a-Si	amorphous Silicon.
ABS	Acrylonitril-Butadien-Styrol, a polymer
Albedo	Albedo is the ratio of the electromagnetic radiation power that is diffusively reflected to an observer to the incident electromagnetic radiation power.
BIPV	building integrated photovoltaics
CZ-Si	Singlecrystalline Silicon that is produced by the Czochralski process.
CIS	$CuInSe_2$
CVD	chemical vapour deposition, a surface is coated in a specific process.
DCS	Dichlorosilane
EG-silicon	electronic grade silicon for the electronic industry with a high purification grade.
EVA	Ethylene-Vinylacetate, a copolymer, used for the encapsulation of solar cells in a laminate
HDK	high disperse silica acid
ID	Inner Diameter saw
n.d.	no data
CED	cumulative energy demand
kWp	Kilowatt Peak. The basic unit for the characterisation of a PV plants capacity. The capacity is measured in a standardized test with a temperature of 25°C, and an irradiation of 1000 W/m^2).
Laminate	Type of solar modules without a frame
sc-Si	singlecrystalline silicon
MG-silicon	metallurgical grade silicon; technical product with a purity of > 96-98%
MJ-eq	Mega Joule primary energy equivalents.
Module	PV-panels are quite often labelled as modules. Here module is also used to describe one set of unit process raw data for the life cycle inventory.
MWp	Megawatt Peak.
mc-Si	multicrystalline Silicon
ppmw	parts per million by weight
PTFE	Polytetrafluoroethylen, „Teflon“
PV	Photovoltaics
STC	Silicone tetrachloride
SoG-Si	solar grade silicon, purified silicon with a purification grade between =>MG- and =>EG-silicon, specifically produced for photovoltaics applications.
SWISSOLAR	Schweizerischer Fachverband für Sonnenenergie
TCS	Trichlorosilane
UCTE	Union for the Co-ordination of Transmission of Electricity

VSE	Verband Schweizerischer Elektrizitätsunternehmen

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