Life Cycle Assessment of Photovoltaics; Update of the ecoinvent Database

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ABSTRACT

Recently, the data for photovoltaics in the ecoinvent database have been updated on behalf of the European Photovoltaics Industry Association and the Swiss Federal Authority for Energy. Data have been collected in this project directly from manufacturers and were provided by other research projects. 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 grid-connected 3 kWp plants in the year 2005.

The inventories cover mono- and polycrystalline cells, amorphous and ribbon-silicon, CdTe and CIS thin film cells. Environmental impacts due to the infrastructure for all production stages and the effluents from wafer production are also considered. The ecoinvent database is used as background database.

Results from the LCA study are presented, comparing different types of cells used in Switzerland and analysing also the electricity production in a range of different countries. It is also discussed how the environmental impacts of photovoltaics have been reduced over the last 15 years, using the CED indicator. The consistent and coherent LCI datasets for basic processes make it easier to perform LCA studies, and increase the credibility and acceptance of the life cycle results. The content of the PV LCI datasets is available via the website www.ecoinvent.org for ecoinvent members.

INTRODUCTION

Life cycle assessment (LCA) has proved to be a powerful tool for the environmental improvement of production processes in the energy sector. However, the increased use of the LCA method to analyse systems is hindered by the lack of agreement on the use of methods and by the limited availability of life cycle inventory (LCI) data. Recently, the data for photovoltaics in the ecoinvent database have been updated on behalf of the European Photovoltaics Industry Association and the Swiss Federal Authority for Energy ([1]).

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 ([2]). Updated LCI data of single- and multicrystalline PV technologies were investigated within the framework of the CrystalClear project based on

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

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 v2.0 and documented according to the ecoinvent requirements ([1]). The following unit process raw data have been 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)
- 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

New thin film cells technologies 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 had been investigated [3]. For the ecoinvent data v2.0 we investigated the PV technology mixes for several European countries using the specific electricity yields in each country based on published irradiation levels ([4]). Also yields in selected non-European countries (e.g. in Asia, Australia and North-America) were considered for a rough extrapolation of the European PV model to PV installations in those countries. However, different electricity/energy mixes for the manufacturing upstream chains have not been modelled for different country-specific cases but only the average European chain was investigated in detail.

SYSTEM BOUNDARIES

Sixteen different, grid-connected photovoltaic systems were studied. These are different small-scale plants of $3kW_p$ capacity and operational in the year 2005 in Switzerland (see Tab. 1).

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 average PV electricity mix in Switzerland considers the actual performance of the installed plants ([5]), while data for specific types of PV plants (e.g. laminate and panel, single- or multicrystalline) can be used for comparisons of different technologies. The calculations in ([4]) are performed for PV plants located in Berne with 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. These results have been used for our technology specific assessments (e.g. in Fig. 3).

The actual PV electricity mixes in 2005 with different types of PV power plants in several countries are also modelled. The yield data for PV electricity mixes in other countries are based on a publication for optimum installations ([4]) and a correction factor which takes into account an actually lower yield of average installations in Switzerland compared to this optimum installation ([1]).

Tab. 1: Overview of the types of photovoltaic 3 kWp systems investigated for an installation in Switzerland

Installation	Cell type	Panel type 1)
Slanted roof	sc-Si	Panel
	mc-Si	Panel
	a-Si	Panel
	ribbon-Si	Panel
	CdTe	Panel
	CIS	Panel
	sc-Si	Laminate
	mc-Si	Laminate
	a-Si	Laminate
	ribbon-Si	Laminate
Flat roof	sc-Si	Panel
	mc-Si	Panel
Façade	sc-Si	Panel
	mc-Si	Panel
	sc-Si	Laminate
	mc-Si	Laminate

1) Panel = mounted; Laminate = integrated in the roof construction, sc-Si = singlecrystalline silicon, mc-Si = multicrystalline silicon.

The amount of panels necessary for a 3 kW_p plant is calculated with the cell efficiency and the cell surface of the panel. The surface areas for a 3 kWp-plant are shown in Tab. 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. 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	7.6%	7.1%	9306	1	42.2	39.2	71

*a 7.1% CdTe panel efficiency assumes a 90% contribution of Antec (6.9% efficient) modules and 10% of First Solar (9%% efficient) modules in Switzerland in 2005.

All subsystems shown in Fig. 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, assuming 30 years operational lifetime for the plant. The basic assumptions for each of these unit processes are described in the report. We considered the following items for each production stages as far as data were 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.

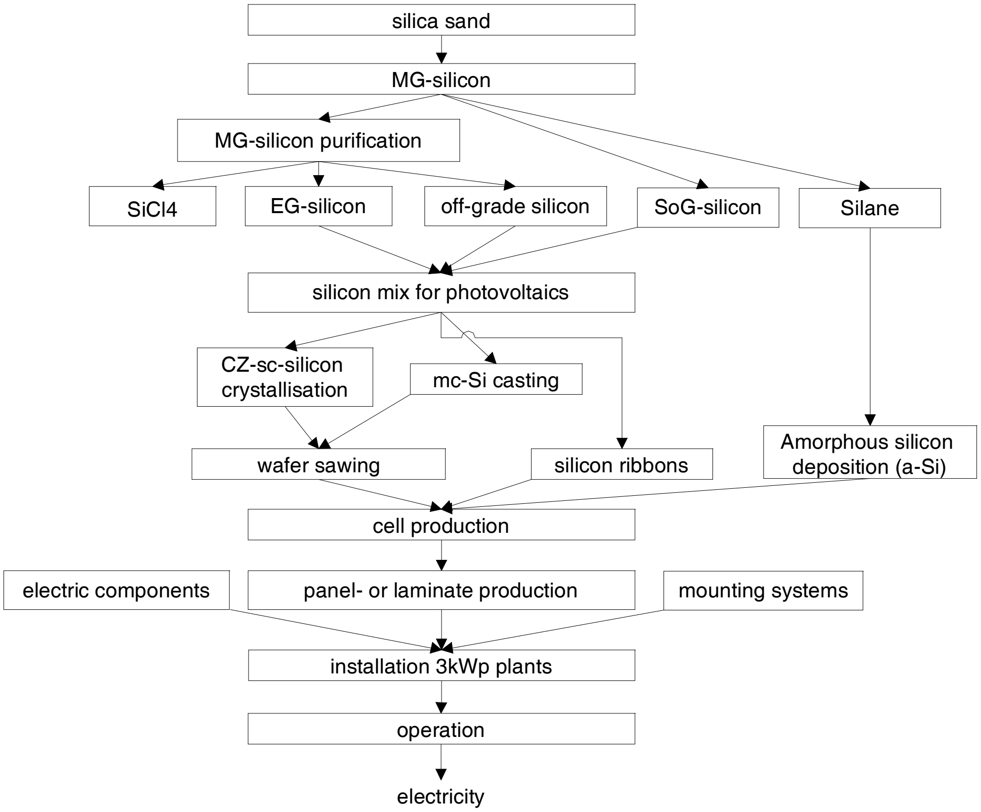

Fig. 1: Different sub systems investigated for the production chain of silicon cells based photovoltaic power plants installed in Switzerland. MG-silicon: metallurgical grade silicon, EG-silicon: electronic grade silicon, SoG-silicon: solar-grade silicon, a-Si: amorphous silicon

All subsystems shown in Fig. 2 are included within the system boundaries for thin film PV power plants. All inputs (semiconductor metals, panel materials and auxiliary materials) for the production of thin film cells, laminates and panels are investigated in other reports of the ecoinvent project ([6]). Thus, in the specific report for PV we only described the process stages starting from the laminate and panel production.

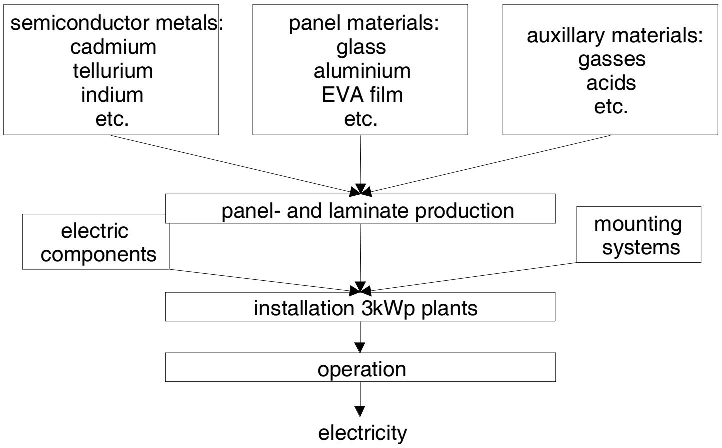

Fig. 2: **Different sub systems investigated for thin film (CIS and CdTe) photovoltaic power plants installed in Switzerland**

RESULTS

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. 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 [7] as the reference system. Fig. 3 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 characteristics like type of installation, type of cells, type of panel (mounted, on Fig. 3) or laminates (integrated) are the key factors for determining the relative differences in results illustrated in this figure.

Fthenakis and Alsema have earlier reported pay-back times of 2.2 and 1 year for multi-Si and CdTe panels, respectively, under an irradiation of 1700 kWh/m2yr, which is the South European average [8]. Adjusted to the irradiation level of 1117 kWh/m2/yr in Switzerland this would correspond to 3.3 year for multi-Si and 1.5 year for CdTe.

When we compare the corrected EPBT values from Fthenakis and Alsema for multi-Si (3.3 yr) with our results for "slanted roof, multi-Si, laminated, integrated" systems (2.7 yr) we see that our result is lower. Reasons for this difference are the technology improvements in multi-Si module production since the analysis by Fthenakis and Alsema (e.g. reduced silicon consumption), and that we assumed a 7.1% efficiency for CdTe PV, whereas Fthenakis and Alsema used a 9% efficiency. Further analysis shows that energy requirements for the BOS are considerably higher in our study, for a number of reasons (heavier mounting structures, detailed estimate for inverter electronics).

Furthermore, the share of BOS for the total results in [8] is much lower than in our study and the difference between CdTe and multi-Si panels is only small. CdTe panels have in our study only 60% of the efficiency compared to multi-Si, which result in much higher specific share of mounting structures for the thin-film. In our study the BOS of CdTe amounts to 44% while [8] gives only a share of about 19%.

Comparison of the EPBT values for CdTe technology between Fthenakis and Alsema (1.5 yr), on the one hand, and our results on the other hand (2.7 yr, see fig. 3) is rather difficult because of differences in the considered module production technology, data sources, and module efficiency (9% vs. 7.1%). Tentatively, we could conclude that our higher energy requirements for the mounting structure specific to Switzerland, in combination with lower module efficiencies, explains a large part of our higher EPBT result for thin film PVs.

We caution that ecoinvent data are a careful analysis of the situation in Switzerland for the year 2005. They do not represent a reference for the current state-of-the-art of thin film PV mix in other countries, and should not be casually extrapolated to other situations or boundary conditions.

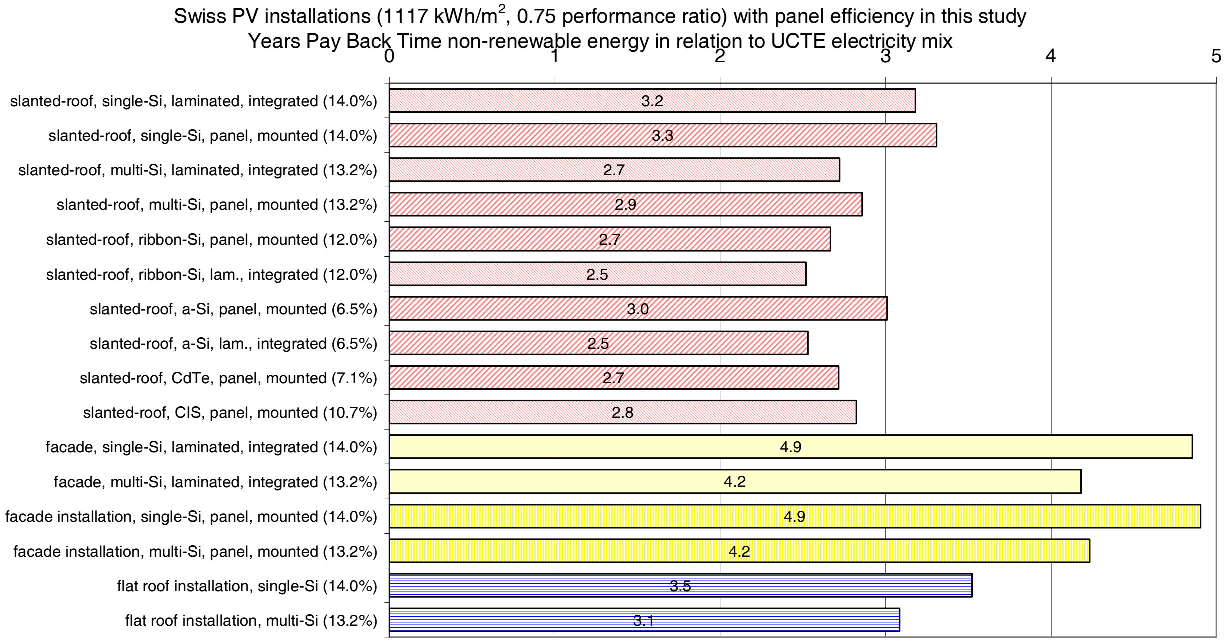

Fig. 3: **Energy pay back time of 3 kWp photovoltaic power plants operated in Switzerland in relation to the UCTE electricity mix (results with ecoinvent data v2.0). Red for slanted roof, yellow for façade, blue for flat roof. Efficiencies in this, are shown in the captions above.**

Development of LCA results

Fig. 4 shows the development of results for the cumulative energy demand of photovoltaic electricity in this study compared to previous Swiss studies. The figure shows also the increase in installed capacity in Switzerland. 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.

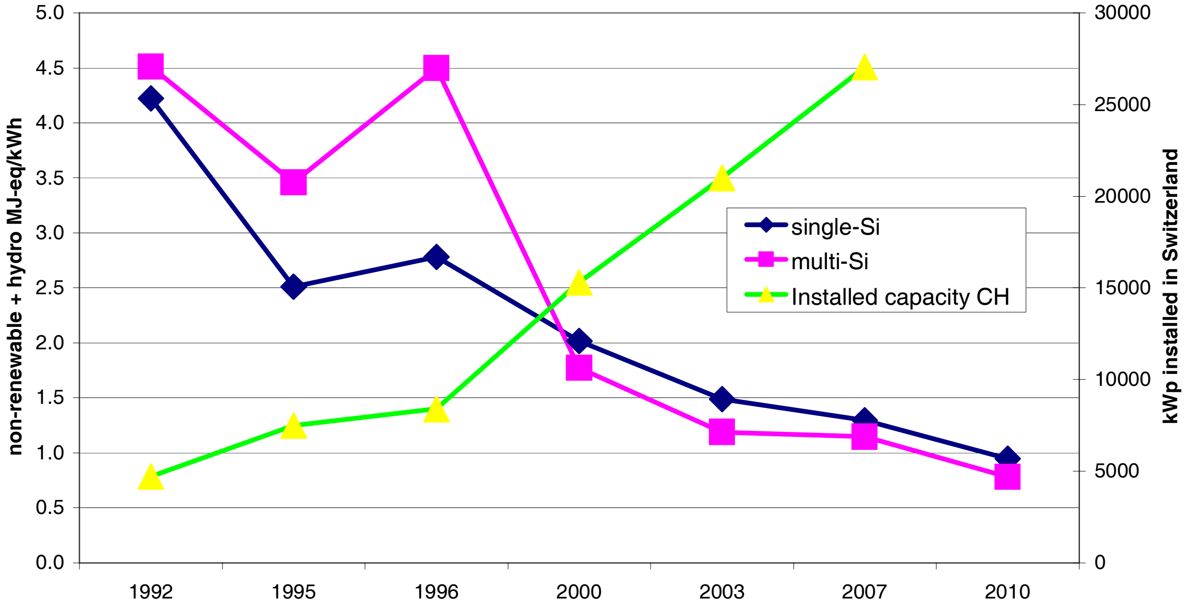

Fig. 4 **Cumulative energy demand of the life cycle inventory for photovoltaic power production in this study (2007) and comparison with previous Swiss studies. Data for 2010 were forecasted with ecoinvent data v1.0 in 2003 [3, 9-11]**

Comparison of different countries

Fig. 5 shows the global warming potential (100a) for photovoltaic power plants operated 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. CO_2-equivalent emission per kWh might be as low as 50 grams per kWh to the grid in the average case investigated for Spain. They will be even lower if optimum installations with best performance ratios are taken into account.

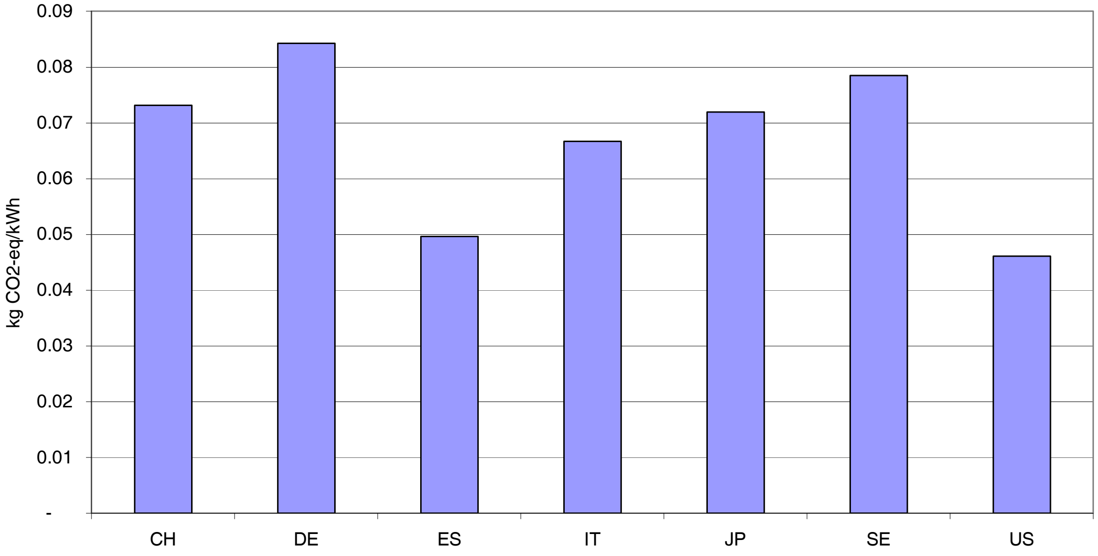

Fig. 5 **Global warming potential in kg CO_2-eq per kWh for the average (2005) photovoltaic electricity mixes in different countries (results with ecoinvent data v2.0)**

CONCLUSIONS

The life cycle inventories of photovoltaic power plants performed for the ecoinvent data v2.0 can be assumed to be representative for photovoltaic plants and for the average photovoltaic mix in Switzerland and in other European countries in the year 2005. The analysis of the results shows that it is quite important to take the real market situation (raw material supply, electricity, etc.) into account. All major PV technologies have been investigated in this study in a consistent and comparable way.

Differences in comparison to other studies are mainly due to different data sources, and assumptions for irradiation, efficiencies, and mounting structures. These factors must also be taken into account along with the technology development level for comparisons with other types of electricity generation. Other factors like differences in the share of imports from different PV producing regions or types of PV cells have not been modelled separately for each country. It should be considered that the inventory may not be valid for wafers and panels produced outside of Europe or the 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 major producing countries (e.g. Japan).

Our study shows that also the balance of system components play a more and more important role for the comparison of different types of PV technologies with different efficiencies and thus different sizes of mounting systems for the same electric output. The low efficiency systems need larger amounts of mounting structure and cabling which partly outweighs the better performance per kWp of module alone.

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REFERENCES

1. Jungbluth N & Tuchschmid M, *Photovoltaics*, in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, Dones R, (Editor). 2007, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories: Dübendorf, CH. p. 180. www.ecoinvent.org.
2. de Wild-Scholten MJ & Alsema EA. *Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production*. in *Proceedings of the Materials Research Society Fall 2005 Meeting*. 2005. Society MR, Boston, USA. Retrieved from www.mrs.org.
3. Jungbluth N, *Photovoltaik*, in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, Dones R, (Editor). 2003, Final report ecoinvent 2000 No. 6-XII, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories: Dübendorf, CH. www.ecoinvent.org.
4. Gaiddon B & Jedliczka M, *Compared assessment of selected environmental indicators of photovoltaic electricity in OECD cities*. 2006, This technical report has been prepared under the supervision of PVPS Task 10, PVPS Task 10, Activity 4.4, Report IEA-PVPS T10-01:2006, The compilation of this report has been supported by the French Agency for Environment and Energy Management, ADEMEIEA: Hespul, Villeurbanne, France.
5. Hostettler T, *Solarstromstatistik 2005 mit Sonderfaktoren.* Bulletin SEV/AES, 2006. **10**(2006).
6. Classen M, Althaus H-J, Blaser S, Doka G, et al., *Life Cycle Inventories of Metals*. 2007, CD-ROM, ecoinvent report No. 10, v2.0, EMPA Dübendorf, Swiss Centre for Life Cycle Inventories: Dübendorf, CH. Retrieved from www.ecoinvent.org.
7. Frischknecht R, Tuchschmid M, Faist Emmenegger M, Bauer C, et al., *Strommix und Stromnetz*, in *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, Dones R, (Editor). 2007, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories: Dübendorf, CH. www.ecoinvent.org.
8. Fthenakis V & Alsema E, *Photovoltaics Energy payback times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status.* Progress in Photovoltaics: Research and Applications, 2006. **2006**(14): p. 275-280.
9. Frischknecht R, Hofstetter P, Knoepfel I, Dones R, et al., *Ökoinventare für Energiesysteme. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz.* 1994, Auflage, 1, Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich

und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut Villigen: Bundesamt für Energie (Hrsg.), Bern.

10. Frischknecht R, Bollens U, Bosshart S, Ciot M, et al., *Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*. 1996, Auflage, 3, Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut, Villigen: Bundesamt für Energie (Hrsg.), Bern, CH. Retrieved from www.energieforschung.ch.
11. Jungbluth N & Frischknecht R, *Literaturstudie Ökobilanz Photovoltaikstrom und Update der Ökobilanz für das Jahr 2000*. 2000, Programm Aktive Sonnenenergienutzung: Photovoltaik Bericht Nr. 39489, ESU-services for Bundesamt für Energie: Uster. p. 43. Retrieved from www.esu-services.ch.