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Broader Perspectives

Life Cycle Assessment of Crystalline Photovoltaics in the Swiss ecoinvent Database

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This paper describes the life cycle assessment (LCA) for photovoltaic (PV) power plants in the new ecoinvent database. Twelve different, grid-connected photovoltaic systems were studied for the situation in Switzerland in the year 2000. They are manufactured as panels or laminates, from monocrystalline or polycrystalline silicon, installed on facades, slanted or flat roofs, and have 3 kW$_p$ capacity. The process data include quartz reduction, silicon purification, wafer, panel and laminate production, mounting structure, 30 years operation and dismantling. In contrast to existing LCA studies, country-specific electricity mixes have been considered in the life cycle inventory (LCI) in order to reflect the present market situation. The new approach for the allocation procedure in the inventory of silicon purification, as a critical issue of former studies, is discussed in detail. The LCI for photovoltaic electricity shows that each production stage is important for certain elementary flows. A life cycle impact assessment (LCIA) shows that there are important environmental impacts not directly related to the energy use (e.g., process emissions of NO_x from wafer etching). The assumption for the used supply energy mixes is important for the overall LCIA results of different production stages. The presented life cycle inventories for photovoltaic power plants are representative for newly constructed plants and for the average photovoltaic mix in Switzerland in the year 2000. A scenario for a future technology (until 2010) helps to assess the relative influence of technology improvements for some processes. The very detailed ecoinvent database forms a good basis for similar studies in other European countries or for other types of solar cells. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: allocation; ecoinvent; electricity mixes; life cycle assessment; LCA; multi-output process; photovoltaic; Switzerland.

1. INTRODUCTION

Life cycle assessment (LCA) aims at comparing and analysing the environmental impacts of products and services. The International Organization for Standardization (ISO) has standardized the basic principles.[1] An LCA

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consists of four steps. The *goal and scope definition* describes the underlying questions, the system boundaries and the definition of a functional unit for the comparison of different alternatives. The flows of pollutants, materials and resources are investigated and recorded in the *inventory analysis*. The elementary flows (emissions and resource consumption) are described, characterized and aggregated for different environmental problems during the *impact assessment*. Final conclusions are drawn during the *interpretation*. Normally LCA aims to analyse and compare different products, processes or services that fulfil the same utility (e.g., photovoltaics against nuclear power). It is used for hot spot analysis, product or process improvement, marketing and environmental policy.

LCA studies for photovoltaic power plants have a long tradition[2–14] of more than 15 years. The published studies show a high variation in results and conclusions. 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 polycrystalline panel. The main reasons for the different LCA results were evaluated in the late 1990s.[15–17] 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 few decades, e.g., for the efficiency of cells, the amount of silicon required, and the actual capacity of production processes. The data availability is a major problem for establishing a high-quality inventory, because only a few producers provide reliable and verifiable data.

The Swiss life cycle inventory for photovoltaics,[12,13] which formed the basis for many studies in this research area, has recently been updated. This article presents the latest results from this research. The terms of use of this database do not allow a full publication of the inventory data in such an article, nor would this be possible due to the extent of the information, but all assumptions are documented in detail in the ecoinvent reports.[18,19]

The Swiss Centre for Life Cycle Inventories has combined and extended different LCI databases. The goal of the ecoinvent 2000 project was to provide a set of unified and generic LCI data of controllable quality and full transparency. The project aimed at updating and extending the Swiss '*Ökoinventare von Energiesystemen*'.[12] The data are mainly investigated for Swiss and Western European conditions. The LCA database ecoinvent contains more than 2500 datasets of goods and services from the energy, transport, building materials, chemicals, pulp and paper, waste treatment and agricultural sectors. Several new materials and services have been investigated as compared to the 1996 version.

2. GOAL, SCOPE AND BACKGROUND

Twelve different, grid-connected photovoltaic systems were studied: ten different small-scale plants of 3 kW_p capacity and installed in the year 2000 in Switzerland, and two slanted roof plants based on a scenario with a future production technology that might be applied until 2010 (Table 1). For this scenario a reduction of energy

Table I. Overview of the types of photovoltaic 3 kW_p systems investigated

Installation	Cell type	Panel type*
Slanted roof	mc-Si	Panel
	pc-Si	Panel
	mc-Si	Laminate
	pc-Si	Laminate
	mc-Si, future	Laminate
	pc-Si, future	Laminate
Flat roof	mc-Si	Panel
	pc-Si	Panel
Facade	mc-Si	Panel
	pc-Si	Panel
	mc-Si	Laminate
	pc-Si	Laminate

*Panel = mounted; laminate = integrated in the roof construction; mc-Si = monocrystalline silicon; pc-Si = polycrystalline silicon.

consumption in different stages has been assumed based on minimum figures critically evaluated from the literature.

The plants differ according to the cell type (monocrystalline and polycrystalline silicon, mc-Si and pc-Si, respectively), and the place of installation (slanted roof, flat roof and facade). Slanted roof and facade 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 2000 with different types of PV power plants in Switzerland has also been modelled.

3. LIFE CYCLE INVENTORY

All sub-systems shown in Figure 1 are included within the system boundaries. The process data include quartz reduction, silicon purification, wafer, panel and laminate production, manufacturing of converter and mounting infrastructure and 30 years of operation. Furthermore transport of materials, of energy carriers, of semi-finished products and of the complete power plant, as well as waste treatment processes for production wastes and end of life wastes are considered in all process stages. The infrastructure for all production facilities with its land use has also been roughly assessed. Air- and waterborne process-specific pollutants are included as well. The photovoltaic system is divided into unit processes for each of the process stages shown in Figure 1. The basic assumptions for each of these unit processes are described in the following sections. Table IV at the end of this section shows the most important parameters for the inventory analysis.

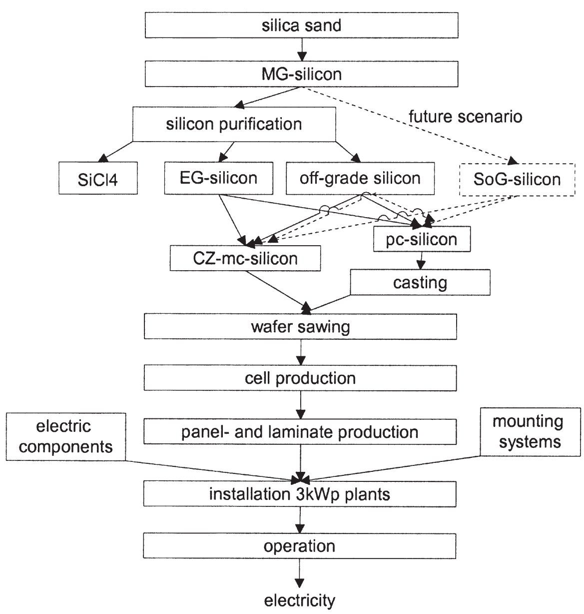

Figure 1. Different sub-systems investigated for photovoltaic power plants installed in Switzerland. The future scenario is shown with dotted arrows. MG-silicon: metallurgical grade silicon, EG-silicon: electronic grade silicon, SoG-silicon: solar-grade silicon

3.1 Metallurgical-grade silicon (MG-silicon)

The production of MG-silicon (metallurgical-grade) with a purity of about 99% is based on carbothermal reduction of silica sand, using petrol coke, charcoal and wood chips as reduction agents. The consumption of reducing agents, electricity use, 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 production in Europe takes place in Norway, but the exact share is not known. The Norwegian electricity mix (with a high share of hydroelectric power) was considered for the inventory (see Table IV). Other producers in France, which use mainly nuclear power, could not be considered because data were not available.

By-products of the charcoal production process such as gases, wood spirit or acetic acid are disregarded because they are of minor importance for the economic performance of the plant. They do not bear emissions and requirements from the process and are not allocated to the charcoal as a waste output. 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.[20]

3.2 Silicon purification

MG-silicon is converted to EG-silicon (electronic-grade) in the Siemens process (via reaction to trichlorosilane). Inventory data are based on information available for the most important producer in Europe, located in Germany. Thus, it can not be regarded as representative of other technologies or production sites. Electricity production is calculated with the in-house mix of the production that uses a natural gas co-generation power plant and hydropower.

The purification process provides three different products which are used in three different economic sectors (Figure 2). The environmental impacts of the purification process have to be shared between these three coupled products. In LCA the problem of how to assign the environmental impacts between different couple products is termed the allocation problem. Different approaches to this problem are possible according to the ISO standards. One approach divides all elementary flow according to the revenue formed by the coupled products, thus the product with the highest price gets the highest environmental impact. Another possibility is dividing the elementary flows according to mass flows in the system. Thus, production of hydrogen chloride is allocated to the production of silicon tetrachloride.

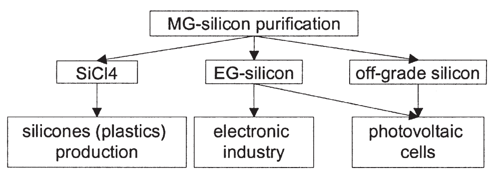

Figure 2. Purification of MG-silicon delivering three different co-products

In several photovoltaic LCAs 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[21] on the basis of the revenues of EG-silicon and $SiCl_4$. 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'.[22] This rule has been followed for the ecoinvent database. The inputs and outputs of the silicon purification process are shared between all three products.

Table II shows some selected inputs, outputs and the allocation factors of the MG-silicon purification process as an example. The first three rows 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 six rows show examples for some inputs required for the purification of 1 kg 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 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. 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.

Table II. Example of the multi-output process raw data of the purification of 1 kg MG-silicon and allocation factors used for the three co-products[19]

	Name	Location	Unit	MG-silicon, to purification DE (kg)	silicon, electronic grade, at plant DE (%)	silicon, electronic grade, off-grade, at plant DE (%)	silicon tetrachloride, at plant DE (%)	Allocation criteria
allocated products	silicon, electronic-grade, at plant	DE	kg	$6{\cdot}76 \times 10^{-1}$	100	0	0	
	silicon, electronic-grade, off-grade, at plant	DE	kg	$8{\cdot}44 \times 10^{-2}$	0	100	0	
	silicon tetrachloride, at plant	DE	kg	$1{\cdot}20 \times 10^{0}$	0	0	100	
technosphere	MG-silicon, at plant	NO	kg	$1{\cdot}00 \times 10^{0}$	71·1	8·9	20·0	Material balance
	polyethylene, HDPE, granulate, at plant	RER	kg	$6{\cdot}37 \times 10^{-4}$	72·0	2·4	25·6	Revenue all products
	hydrochloric acid, 30% in H_2O, at plant	RER	kg	$2{\cdot}00 \times 10^{0}$	48·4	1·6	50·0	Stoichiometric calculation
	natural gas, bumed in boiler condensing modulating >100 kW	RER	MJ	$1{\cdot}22 \times 10^{2}$	96·8	3·2	0	Revenue purified silicon
	electricity, natural gas, at combined cycle plant, best	RER	kWh	$8{\cdot}66 \times 10^{1}$	96·8	3·2	0	Revenue purified silicon
	electricity, hydropower, at run-of-river power plant	RER	kWh	$2{\cdot}74 \times 10^{1}$	96·8	3·2	0	Revenue purified silicon
	price (€)	GLO		70·36	75·00	20·00	15·00	
	revenue (€)	GLO		70·36	50·67	1·69	18·00	

With the dataset 'MG-silicon, to purification' and its allocation factors, three unit process datasets are generated for the ecoinvent database, namely for 'silicon, electronic-grade, at plant', 'silicon, electronic-grade, off-grade, at plant', and 'silicon tetrachloride, at plant'. Thereby, all inputs and outputs are multiplied by the respective allocation factor and divided by the respective amount of the co-product to give the flows per unit mass of product. Table III shows an example of the derived unit process raw data.

Table III. Derived unit process raw data for the three co-products of 'MG-silicon, to purification'[19]

	Name	Location	Unit	silicon, electronic grade, at plant (kg)	silicon, electronic-grade, off-grade, at plant (kg)	silicon tetrachloride at plant (kg)
allocated products	silicon, electronic-grade, at plant	DE	kg	1	0	0
	silicon, electronic-grade, off-grade, at plant	DE	kg	0	1	0
	silicon tetrachloride, at plant	DE	kg	0	0	1
technosphere	MG-silicon, at plant	NO	kg	1·05	1·05	0·2
	polyethylene, HDPE, granulate, at plant	RER	kg	$6{\cdot}79 \times 10^{-1}$	$1{\cdot}8 \times 10^{-1}$	$1{\cdot}36 \times 10^{-4}$
	hydrochloric acid, 30% in H_2O, at plant	RER	kg	1·4	0·4	0·8
	natural gas, bumed in boiler condensing modulating > 100 kW	RER	MJ	174·2	46·5	
	electricity, natural gas, at combined cycle plant, best	RER	kWh	124·1	33·1	
	electricity, hydropower, at run-of-river power plant	RER	kWh	39·2	10·5	

This approach is a simplification, because it is 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 mc-silicon, see Section 3.5) and wafer sawing. These scraps are sold and used directly in the casting process.

The inventory for the year 2000 assumes a mix of 50% off-grade silicon and 50% EG-Si. This reflects the fact that due to a crisis in the electronics industry EG-Si has been sold to the PV industry at a particularly low price. This situation might change rapidly once the demand for EG-Si increases again.

3.3 Solar-grade silicon (SoG-silicon)

A future scenario for the production of solar-grade (SoG) silicon has been assumed based on publications for experimental processes. Different ideas exist for the design of such process. The electricity consumption reported in the literature ranged from 15 to 90 kW h/kg. Here we assume an electricity use of 30 kW h/kg which is approximated with the European UCTE mix. Further quantitative data for the use of chemicals and materials in the process were not available, thus such inputs could not be considered in the inventory. It has to be noted that in 2000 no SoG-Si was on the market, even though possible production routes have been described 20 years ago.[23] So far technological and economic constraints have hindered the installation of such production facilities. For the future scenario an input of 50% solar-grade silicon and 50% off-grade silicon to casting or CZ-Si production is assumed.

3.4 Casting

EG-silicon, off-grade silicon and SoG silicon are molten and cast into reusable moulds. Wafers can be directly produced from these polycrystalline blocks. 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.

3.5 Czochralski monocrystalline silicon (CZ-mc-silicon)

The EG-silicon is molten and a growing crystal is slowly extracted from the melting pot. Inventory data are based on literature information and environmental reports of one producer in Germany, because other primary information was not available. The product is monocrystalline silicon. Data for electricity consumption range between 48 and 670 kW h/kg. For this study about 120 kW h/kg has been assumed, based on information provided by the company Wacker in Germany. 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. For the future scenario a reduction of the electricity consumption rate in the range of lowest figures from literature has been assumed (Table IV).

3.6 Wafer sawing

The silicon columns are sawn into wafers of 300 μm thickness. 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 air- and waterborne pollutants are considered, based on information from the literature and environmental reports. Emissions of NO_x and nitrate due to surface etching with HNO_3 might be important if these etching agents are used, but data for these emissions have been assessed from only one production site. Other producers might apply technologies with etching agents such as NaOH or KOH, or dry etching. Thus these data are not valid for other production sites. The same data have been used for mc-Si and pc-Si wafer production, because full information for pc-Si wafer was not available.

3.7 Solar cell production

Production of solar cells with a size of 10×10 cm includes purification and etching of the wafers. Afterwards wafers are endowed with phosphorus and, after further etching processes, front and rear contacts are printed.

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. Cell efficiencies are estimated with data provided by several different producers for their actual products (see Table IV).

3.8 Panels and laminate production

Solar cells are embedded in layers of ethylvinylacetate (one each on the front and the back). The rear cover consists of a polyester, aluminium and polyvinylfluoride (Tedlar) film. A 4 mm glass poor in iron is used for the front cover. The sandwich is joined under pressure and heat, the edges are purified and the connections are insulated. A connection box is installed. The panel gets additionally an aluminium frame. 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. Possible changes in the mounting infrastructure have not been assessed separately for the future scenario.

3.9 Mounting systems

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

3.10 Converters and electric equipment

Process data for manufacturing the converter and of the electric equipment include construction materials, energy requirement (for converter only), packaging materials (for converter only) and transport services. Electronic components of the converter and electric equipment have not been considered in the inventory due to lack of data.

3.11 Operation of photovoltaic power plants

The average solar irradiation in Switzerland is about 1100 kW h per m^2 and year. The photovoltaic plants in operation in Switzerland show an average electricity production[24] of 819 kW h per kW_p for the years 1992–2000. Due to changing meteorological conditions the annual yields ranged between 770 and 880 kW h per kW_p. For the inventory of flat and slanted roof installations only the best 75% plants with an average production of 885 kW h per kW_p have been considered to disregard the less efficient facade installations. An average facade system with vertically oriented panels is calculated to produce 626 kW h per kW_p. Water consumption (for cleaning the panels once a year) is included in the inventory.

3.12 Dismantling

For the dismantling of photovoltaic power plants standard scenarios used in the ecoinvent project have been taken into account. For larger metal parts of the system and silicon recycling is assumed. No environmental burdens nor credits have been considered for the recycling. In producing processes such materials are also used without a burden from the primary production process. So far no recycled silicon has been used in the year 2000. The remaining parts are incinerated or landfilled.

3.13 Key parameters for life cycle inventories

The full life cycle inventories and all assumptions are documented in the ecoinvent database.[19] Table IV shows the key parameters of the life cycle inventory in ecoinvent Data v1·1.[18] Main changes in comparison to older Swiss inventories are the update of the energy use in EG-silicon production, the location-specific consideration of power consumption throughout the production chain, and the inclusion of many additional process-specific emissions. The material efficiency for silicon in the life cycle has also been improved in the last years. For future plants a best case estimation has been made from the ranges provided for different key parameters in the literature. The actual use of MG-silicon has been calculated in the inventory as 11 and 12·3 kg per kW_p for mc-Si and pc-Si, respectively. These important figures have been verified with top-down data from the photovoltaics industry.[25–27]

Table IV. Key parameters of the life cycle inventory for photovoltaic power production[19]

	Unit	mc-Si	pc-Si	mc-Si future	pc-si future
MG-silicon production					
electricity use, NO (mainly hydro power)	kWh/kg	11	11	11	11
EG-silicon production					
electricity use, DE, plant specific	kWh/kg	103	103	37	37
CZ-silicon production					
electricity use, UCTE-Mix	kWh/kg	123		100	
mc-Si and pc-Si wafer					
thickness wafer	μm	300	300	300	300
sawing gap	μm	200	200	200	200
wafer area	cm^2	100	100	100	100
weight	g	6·99	6·99	6·99	6·99
cell power	W_p	1·65	1·48	1·75	1·57
cell efficiency	%	16·5	14·8	17·5	15·7
use of MG-silicon	g/wafer	19·0	19·2	16·3	18·1
EG-silicon use per wafer	g/wafer	11·2	11·2	9·3	9·3
process energy	kWh/wafer	0·3	0·3	0·15	0·15
mc-Si and pc-Si cells					
process energy	kWh/cell	0·2	0·2	0·11	0·11
panel/laminate, mc-Si/pc-Si					
number of cells	cells/panel	112·5	112·5	112·5	112·5
panel area	cm^2	12529	12529	12529	12529
active area	cm^2	11250	11250	11250	11250
panel power	W_p	185	166	197	177
efficiency production	%	97%	97%	97%	97%
use of cells mc-Si/pc-Si	cells/kW_p	608	677	571	637
process energy	MJ/kW_p	0·23	0·26	0·20	0·23
3kW_p-plant					
panel area	m^2/3kW_p	18·2	20·3	17·1	19·1
operation					
yield, slope-roof	kW h/kW_p	885	885	885	885
yield, facade	kW h/kW_p	626	626		
yield, CH PV electricity mix	kWh/kW_p	819	819		

mc-Si = monocrystalline sillicon, pc-Si = polycrystalline sillicon.

4. RESULTS AND DISCUSSION

4.1 Selected results for process stages

The first step for the discussion of results is an evaluation of elementary flows over the life cycle. (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 v1·1.) Therefore, emissions and resource uses are added up for all stages in the life cycle. Results are presented, e.g., for one kW h of electricity. Such result tables can be found in the ecoinvent database. Figure 3 shows the shares of different production stages for some selected elementary flows of a slanted roof installation with a polycrystalline silicon panel. Nitrogen oxides

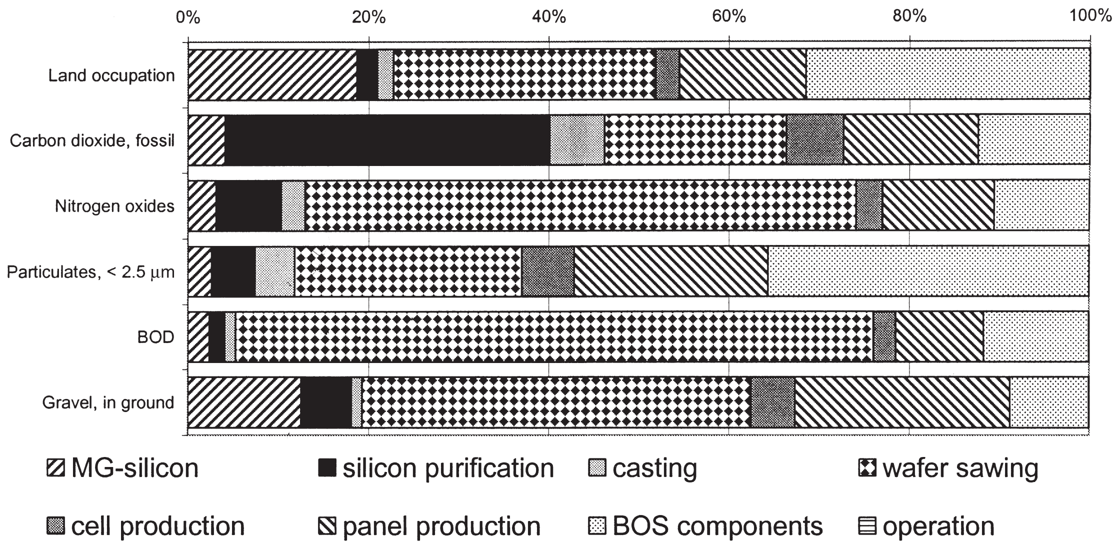

Figure 3. Share of process stages for a Swiss grid-connected, 3 kW_p slanted roof installation with a polycrystalline silicon panel for selected elementary flows of the inventory. BOS-balance of system with mounting system and electric equipment

and BOD are 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.

4.2 Life cycle impact assessment

The next step in the LCA is a life cycle impact assessment (LCIA). The elementary flows (emissions and resource consumption) can be described, characterized and aggregated with different methodologies. Figure 4 analyses the share of the process stages with different LCIA methods.[28] The cumulative energy demand (CED) is calculated for five classes of primary energy carriers (fossil, nuclear, hydro, biomass, and others–wind, solar, geothermal). Differences in the results of different types of cumulative energy demands are mainly due to the consideration of location-specific electricity mixes. During the operation phase the use

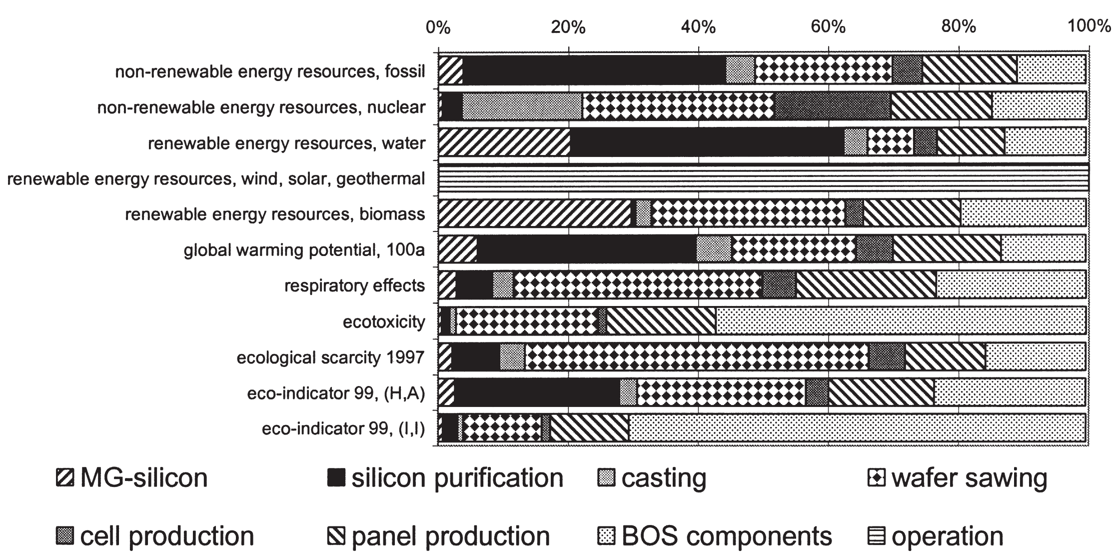

Figure 4. Share of process stages for a Swiss grid-connected, 3 kW_p slanted roof installation with a polycrystalline silicon panel evaluated with different LCIA methods[29–31]

of solar energy dominates the demand in this category. The next LCIA calculates the possible contribution of different gaseous emissions to the problem of climate change (global warming potential).

Further on it is possible to assign a large list of elementary flows to one indicator. Here we use the method of Eco-indicator 99[29] and ecological scarcity 1997.[30] The method Eco-indicator 99 characterises different emissions based on a modelling for the damage caused by these emissions. Thus respiratory effects describe illnesses due to the emission of air pollutants that are inhaled. Different types of damage are finally weighted and summed to one indicator score. Different social perspectives are used by the method for such a weighting. The method ecological scarcity 1997 is based on the environmental policy in Switzerland. It weights different pollutants based on the reduction targets for such emissions.

The installation is quite important for the Individualist perspective of the Eco-indicator 99, which gives a high weighting to the use of metal resources. The Hierachist perspective in the Eco-indicator 99 (H, A) methodology gives a higher weight to the use of energy resources and thus to different stages of the life cycle.

The method of ecological scarcity gives a high weight to air pollutants, e.g., NO_x. This is why wafer production, with its assumed emissions from etching, is quite important. The analysis shows that, depending on the impact assessment method, different types of resource uses or pollutants might be more or less important for the final results, and thus different LCIA methods might provide diverging results.

4.3 Uncertainties of data

The ecoinvent database assigns uncertainty information (standard deviation) to each single elementary flow in the inventory. This makes it possible to analyse the uncertainties of the final results. Uncertainties introduced by the LCIA methodology are not included in this analysis.

Figure 5 evaluates the uncertainties of the LCIA analysis for the Swiss PV mix with a Monte-Carlo (MC) simulation. The highest uncertainties (more than a factor of six) exist for the inventory of radioactive emissions from nuclear power and coal mining. However, the uncertainties in the results for other damage categories of the Eco-indicator 99 (H, A) can be quite high.

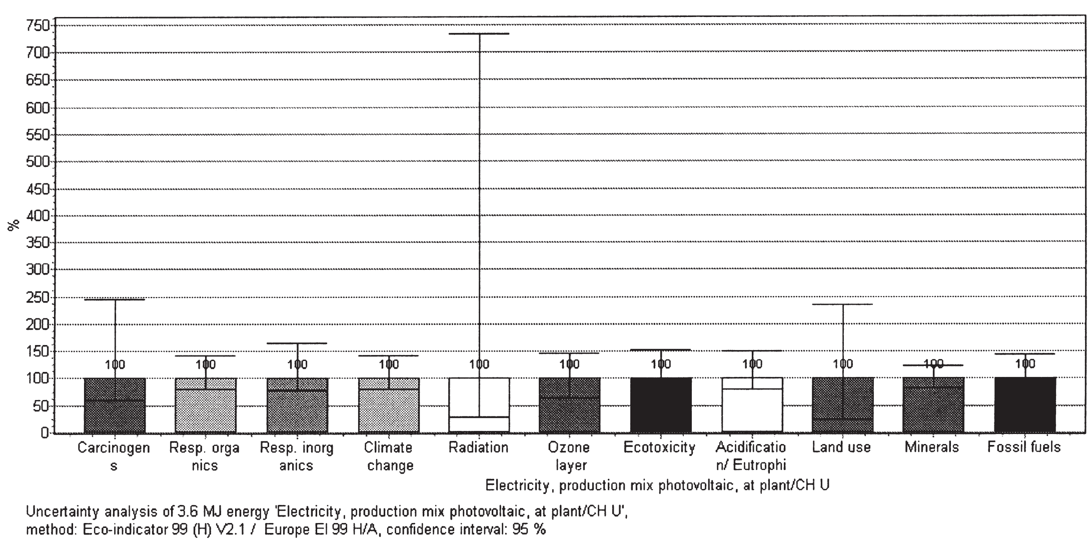

Figure 5. Uncertainties in the LCIA with Eco-indicator 99 (H, A) calculated in a Monte-Carlo simulation for the Swiss PV electricity mix

4.4 Comparison of different photovoltaic plants

Figure 6 shows a comparison of selected cumulative results for different types of electricity production with mc-Si solar cells. The scenario for the future slanted roof power plant shows the lowest flows in the selected categories. Facade installations have higher impacts than flat roof or slanted roof installations due to the lower

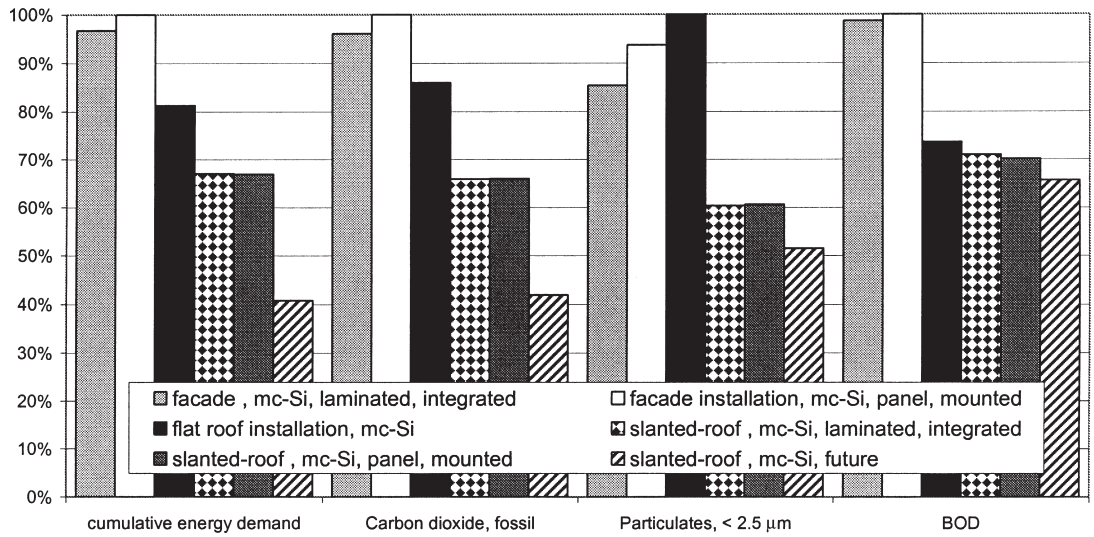

Figure 6. Comparison of selected cumulative results for different types of electricity production with monocrystalline (mc) solar cells

productivity. However, some pollutants might be especially important for flat roof installations that use other types of mounting materials and have a higher weight. Particulates, for example, are emitted during the production of aluminium for the flat roof installations and, in this case study, these installations use more aluminium. Laminates show slightly lower results than the panels because the material consumption, e.g., for frames, is lower.

The environmental impacts for different systems are analysed and compared in Figure 7 based on a valuation with the Eco-indicator 99 (H, A).[29] The highest contribution of environmental impacts in the life cycle is due to the use of fossil energy resources and respiratory effects caused by air emissions of particulates and nitrogen oxides. The highest total score is recorded for the today average of PV plants in Switzerland, because here all installations (including these with sub-optimal performance) are considered for the yield calculation. This case is set to 100%. It is important to keep in mind for a comparison of PV power plants that the actual performance

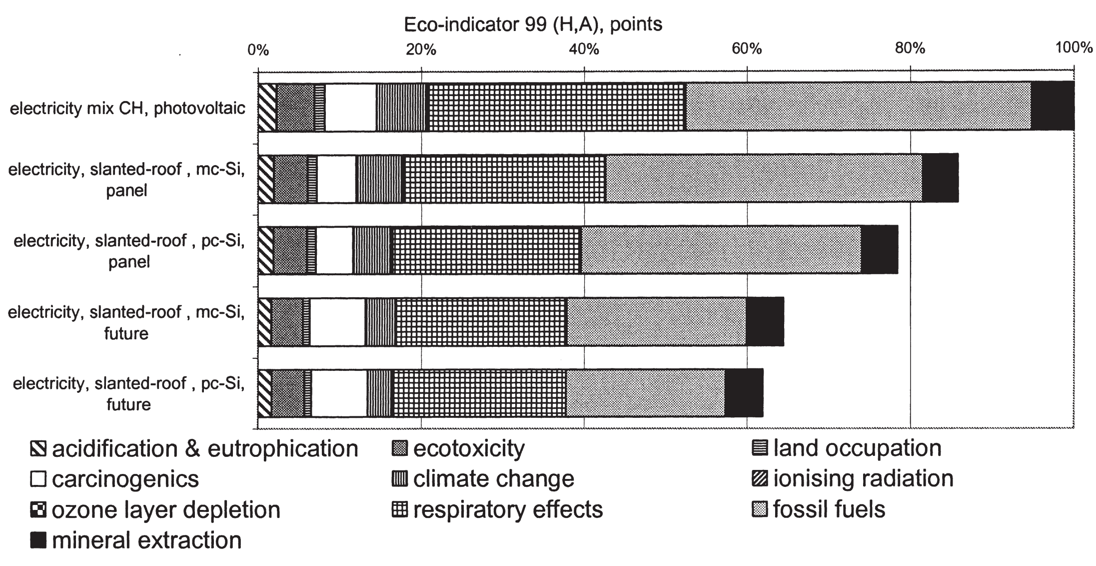

Figure 7. Comparison of Eco-indicator 99 (H, A) scores for different 3 kW_p PV power plants

of installed plants is normally lower than the theoretical performance that could be achieved under optimum conditions.

Plants using monocrystalline cells have higher impact figures than these with polycrystalline cells. The environmental impacts of PV power plants might be further reduced in future if technology improvements in the production processes are realized. A higher share for carcinogenic effects in the two 'future' scenarios results from a different assumption for the electricity supply during the silicon purification stage. Here the average European mix is assumed.

Figure 8 shows a similar analysis with the Swiss LCIA method ecological scarcity 1997.[30] This method gives a high importance to air emissions and here mainly to emissions of NO_x in the life cycle. For the LCIA method emissions to water (nitrogen and chemical oxygen demand) and waste deposits are also important. Again polycrystalline cells show a slightly better environmental performance than monocrystalline cells.

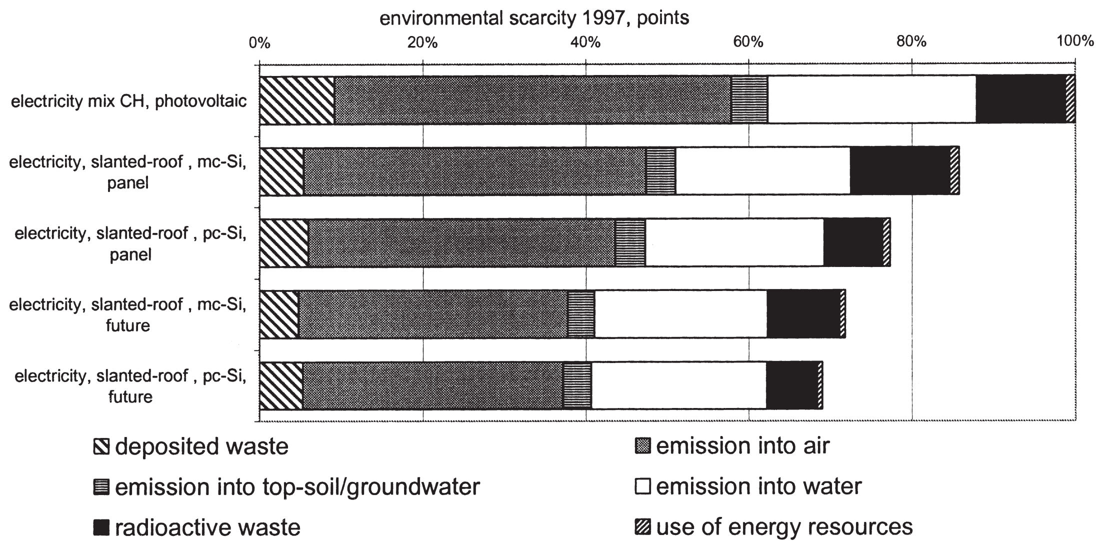

Figure 8. Comparison of environmental scarcity 1997 scores for different 3 kW_p PV power plants

Even with different elementary flows being more or less dominant for the analysis, the comparison between the different plants does not change much in relationship to the LCIA with the Eco-indicator 99 in Figure 7. Thus this result can be seen as quite stable.

The ecoinvent database allows a quantitative assessment and comparison of data uncertainties. Figure 9 evaluates as an example the uncertainties for a comparison of mc-Si and pc-Si power plants. Bars printing to the left indicate an advantage for the mc-Si plant while bars to the right count the Monte-Carlo simulations with an advantage for the pc-Si plants. The Monte-Carlo simulation assumes that many uncertainties go in the same direction for both processes. Radioactive emissions, for example, originate from the electricity uses in the life cycle. The high uncertainty of these figures is not important for the comparison, because both PV plants use the same electricity mixes. The analysis shows that there is no clear result for the comparison, but the majority of runs proves an advantage for pc-Si power plants.

4.5 Comparison with former LCA

Figure 10 evaluates the changes between the new inventory for photovoltaics[19] and the former ETH-data[12] from 1996. The new inventory shows lower impacts. This is mainly due to new assumptions for plant- or region-specific energy use and energy mixes used in the life cycle. Furthermore, air emissions causing respiratory effects are lower, according to the updated analysis.

It is interesting to note that now the differences between monocrystalline and polycrystalline cells are much smaller. This turns the direct comparison of these two types of plants into a small advantage for pc-Si plants. In

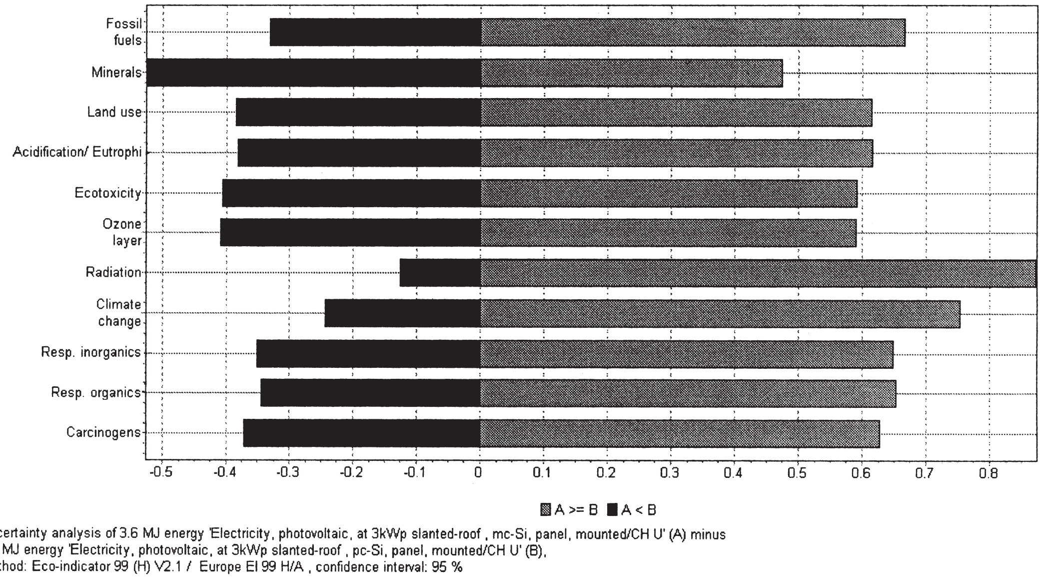

Figure 9. Monte-Carlo simulation for the comparison of mc-Si and pc-Si panels mounted on the roof with the LCIA methodology Eco-indicator 99 (H, A). MC-simulation[32]

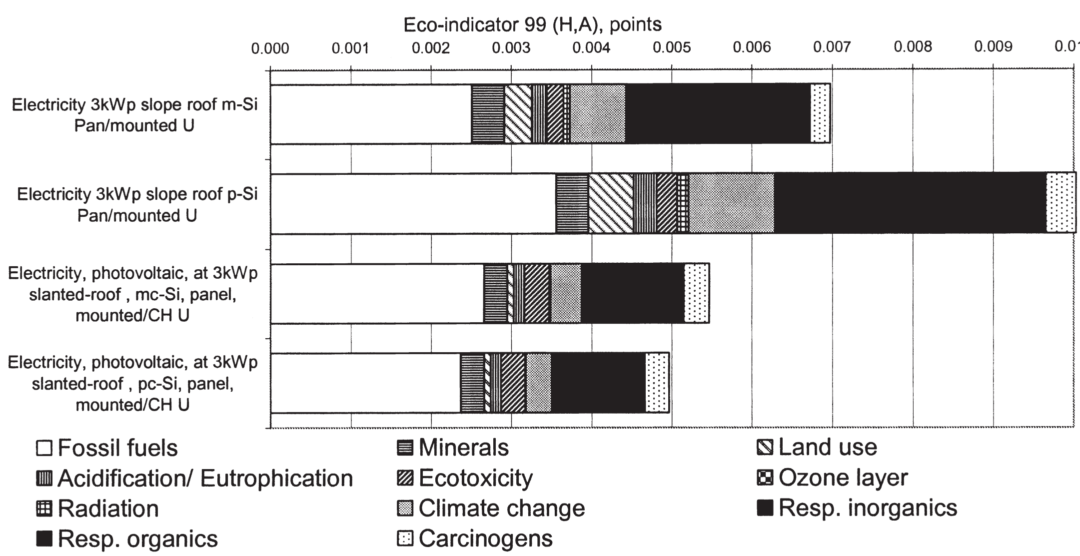

Figure 10. Comparison of updated ecoinvent 2000 data[19] on the lower edge with the ETH-data from 1996[12] on the upper edge. p-Si and pc-Si: polycrystalline; m-Si and mc-Si: monocrystalline[32]

the former inventory the higher production costs for mc-Si plants were outperformed by the better efficiency. With lower energy uses in some stages of the life cycle this difference is no longer that important.

4.6 Comparison with other energy systems

Figure 11 shows a comparison of the photovoltaic power mix in Switzerland with other types of power plants. All systems have been modelled in the ecoinvent database.[33,34] The environmental impacts are evaluated with the cumulative demand of non-renewable energy resources, greenhouse gas emissions, Eco-indicator 99 and ecological scarcity 97. The environmental impacts of photovoltaics are set to 100% in this figure.

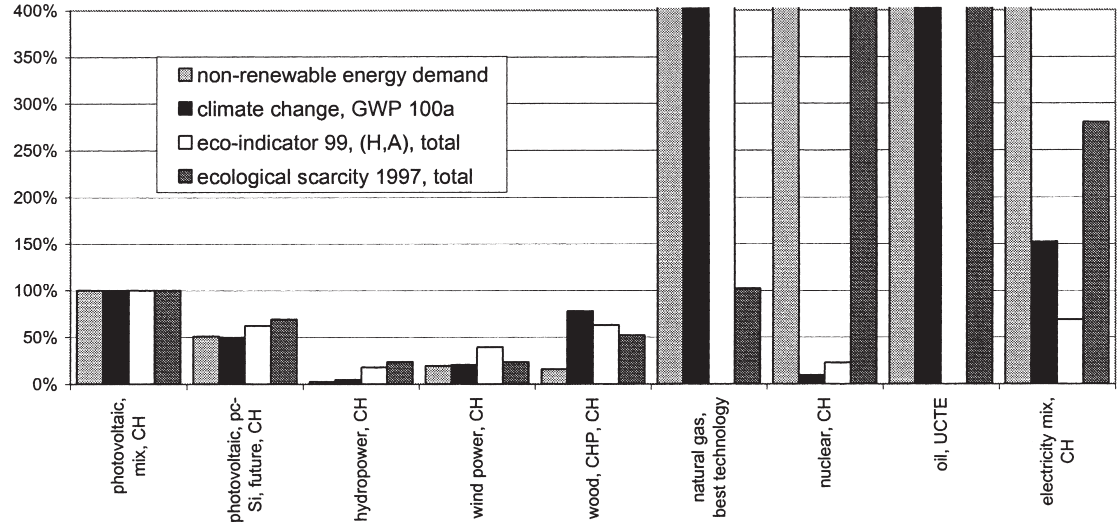

Figure 11. Comparison of the photovoltaic power mix in Switzerland with other types of power plants with different LCIA methodologies.[29–31] CHP—combined heat and power

Other renewable energy systems such as wind, hydro and wood power plants show lower environmental impacts than the photovoltaic power plants with all LCIA methodologies applied here. Power plants using natural gas or oil show much higher impacts. Greenhouse gas emissions for PV range from 39 to 110 g CO_2-eq/kW h with an average for the Swiss mix of 79 g CO_2-eq/kW h. Hydropower has the lowest emissions with about 4 g CO_2-eq/kW h while an oil power plant has the highest with 880 kg CO_2-eq/kW h.

Nuclear power has lower greenhouse gas emissions and Eco-indicator 99 (H, A) scores, but a higher non-renewable energy use and higher ecopoints. The Swiss electricity mix shows lower Eco-indicator 99 (H, A) scores due to the high share of hydro and nuclear power. Thus it can be concluded that PV is better than the conventional power plants based on non-renewable energy resources in many cases. On the other side environmental impacts of alternative renewable energy systems are lower. This is true even for the assumption of an improved PV production chain in the future. This analysis is valid for Switzerland, but not for other countries with other prerequisites (e.g., climatic conditions) for the different energy systems.

4.7 Payback time

An important yardstick for the assessment of renewable energy systems is the estimation of the energy and/or environmental payback time. In some publications the energy payback time was defined as the time until the electricity production of the plant equals the energy use during 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, which shall be demonstrated with some examples. Here we consider a modern natural gas-fired gas combined cycle power plant as the reference system.[35] Environmental impacts are allocated based on the exergy content of the two products, heat and electricity. It is assumed that the use of photovoltaic power plants can avoid the installation of such a facility. Figure 12 shows the payback-time for the indicators non-renewable and non-renewable plus hydro cumulative energy demand. This time is between 3 and 6 years for the different PV plants. This means that the energy demand for producing the photovoltaic plants is as high as the energy demand for the operation of the gas power plant during 3 to 6 years. (There is no direct energy use during operation of the PV plant.) Thus, it is five to ten times shorter than the expected life time of the

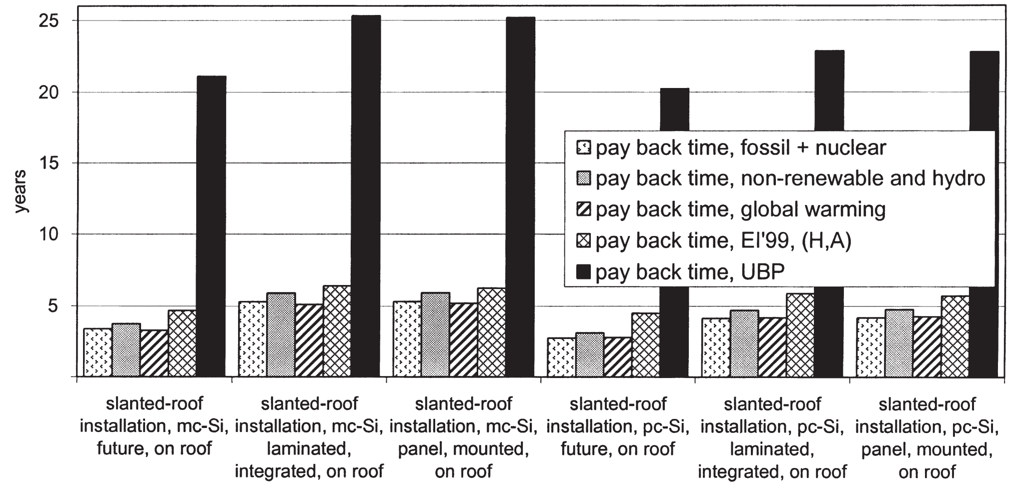

Figure 12. Energy and environmental payback time of 3 kW_p slanted roof photovoltaic power plants in relation to a modern natural gas-fired gas combined cycle power plant

photovoltaic power plants. The environmental payback time for greenhouse gas emissions is similar to this for non-renewable energy resources.

This picture changes if emissions are taken into account. Weighting the impact with the method of ecological scarcity (Umweltbelastungspunkte, UBP) gives an environmental payback time of about 25 years,[28,30] whereas the payback time evaluated with Eco-indicator 99 (H, A) is only slightly higher than for the energy demand.

The picture would also change if other reference systems were considered. This can be assumed with the help of comparing different electricity systems in Figure 11. If we take the Swiss electricity mix as a reference system, the payback time for ecological scarcity is much lower while the payback time calculated with Eco-indicator 99 (H, A) would be higher. These examples show, that it is necessary to discuss the assumptions for a payback time in detail and that the results of such an analysis are quite dependent on these assumptions.

5. CONCLUSION AND OUTLOOK

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 in the year 2000. The average electricity mix considers the actual performance of the installed plants, while plant data (e.g., laminate and panel, monocrystalline or polycrystalline) can be used for comparisons of different technologies. The analysis of the results shows that it is quite important to take the real market situation (raw material supply, electricity, etc.) into account.

Different situations in other countries in comparison with 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 Europe, because production technologies and power mix for production processes might not be the same. For the modelling of a specific power plant or of power plant mixes outside Switzerland it is advisable to consider at least the annual yield ($kW\,h/kW_p$) and if possible also the actual size of the plant in square metres.

The scenario for a future technology helps to assess the potential for improvement of different production steps in the near future (until 2010). Environmental impacts in this scenario are lower by 30–50%. However, the realization of this scenario depends on the development of the market situation for electronics and photovoltaic power. The use of SoG-grade silicon instead of EG-silicon, which would be an important improvement, is possible only if the supply of silicon for photovoltaics cannot be secured in the way it is today or if subsidies are granted to increase the total production of PV panels.

A direct comparison of plants with pc-Si and mc-Si cells with the herewith-inventoried data has only a limited precision. For some production stages data were available for only one of the two types (e.g., NO_x

emissions during wafer sawing and etching). Thus it is unclear if there are more systematic differences between the two types of cells or if the differences have to be explained by accidental variations among individual production plants.

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. It is necessary to evaluate all types of environmental impacts with different LCIA methodologies if photovoltaic power plants are to be compared with other energy systems.

A comparison of photovoltaics with other types of electricity production in Switzerland shows some advantages in relation to conventional power plants. But the comparison is quite dependent on the environmental indicators considered for such an analysis. Photovoltaics have environmental disadvantages in comparison with other renewable technologies, e.g., wind and hydro power. It has to be kept in mind that such a comparison is quite dependent on regional conditions such as solar irradiation or technology standards for conventional power plants. Thus these conclusions are valid only for the Swiss situation.

6. RECOMMENDATION AND PERSPECTIVE

It has to be noted that many emission data in the inventory are based on only one information source. Thus they should be verified with data from other production places. In cases where several information sources were available they can show a large variation. A general problem is that data had to be mixed from different sources.

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. 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 inclusion of results from laboratory testing might give a too optimistic picture on the environmental impacts caused due to the use of photovoltaics today. For reliable and verifiable assessments of the environmental impacts of photovoltaics, the cooperation with the PV industry (silicon purification, cell production) must be improved. Today it is low in comparison with other sectors. A prerequisite for such an analysis is the publication and documentation of verifiable key data about energy uses and emissions in different stages of the life cycle. Studies that do not show such direct unit process data are of little use for the LCA community and for a reliable assessment of environmental impacts.

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 (e.g., thin-film cells or amorphous silicon cells).

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