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2nd International ecoinvent Meeting
Lausanne, March 14, 2008

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energy supply: photovoltaics

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Overview

- System boundaries of ecoinvent data v2.0
- Inventories and up-dates
- Interpretation of results
- Pay-back time
- Country mixes of photovoltaic electricity production
- Conclusions

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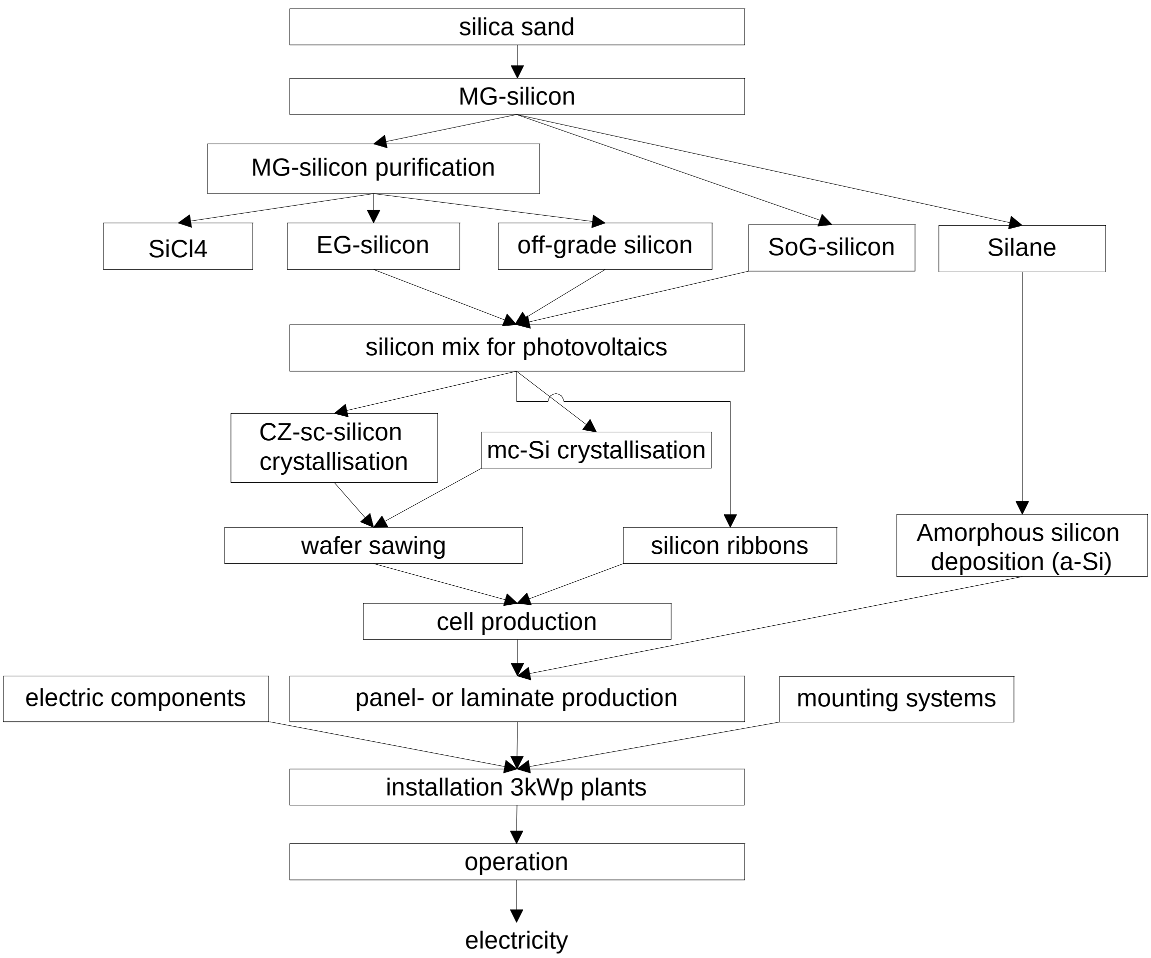
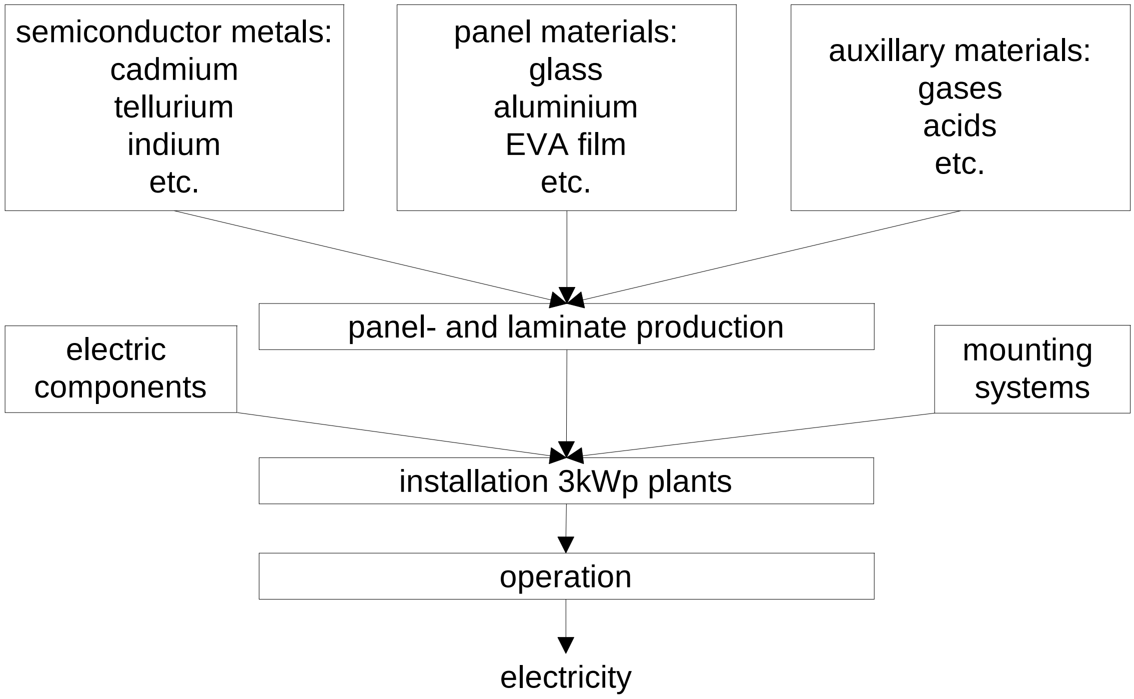
System outline silicon PV



System outline thin-film PV



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Analysed 3kWp plants

Installation	Cell type	Panel type [1)]	Share in Swiss PV mix	Share in other PV mixes
Slanted roof	sc-Si	Panel	26.9%	25.0%
	mc-Si	Panel	36.6%	34.0%
	a-Si	Panel	4.4%	4.5%
	ribbon-Si	Panel	2.7%	2.8%
	CdTe	Panel	1.4%	1.4%
	CIS	Panel	0.2%	0.2%
	sc-Si	Laminate	1.9%	1.0%
	mc-Si	Laminate	2.6%	1.3%
	a-Si	Laminate	0.3%	0.2%
	ribbon-Si	Laminate	0.2%	0.1%
Flat roof	sc-Si	Panel	5.8%	7.7%
	mc-Si	Panel	7.9%	10.5%
Façade	sc-Si	Panel	1.9%	3.8%
	mc-Si	Panel	2.6%	5.2%
	sc-Si	Laminate	1.9%	1.0%
	mc-Si	Laminate	2.6%	1.3%

- **Life cycle inventory from cradle to grave of plants operated 2005 in Switzerland**
- **Adapted data used for average PV electricity mixes in 25 OECD countries**

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Life cycle inventory data

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- Update of all process stages for grid-connected PV in Switzerland for the year 2005
- Crystalline photovoltaics in cooperation with EU Crystal Clear project
- New process route of a modified Siemens process with lower electricity use compared to electronic grade Si accounts for 80% of silicon mix used in PV
- a-Si modules investigated for US production
- CIS with information from Würth Solar
- CdTe with data from US (First Solar) and Germany (Antec)

Life cycle inventory data (2)

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- Wafers, cells and modules are modelled per m^2 in order to facilitate the use of the datasets
- Photovoltaic electricity mixes for 25 countries
- New datasets for fine chemicals used in PV production
- New datasets for coating metals used in thin film cells
- Extensive documentation in English

Electricity production Switzerland Yields in kWh per kWp and year

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- Irradiation in Switzerland about 1100 kWh/m^2 which is representative also for global weighted average
- Electricity yields are quite important for performance
- Factor 3 variation in observed and calculated yields
- Technology specific yields are based on optimum installation in Switzerland
- Yields adaptable by the user for assessments in other locations

	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*

Analysis of process stages: multicrystalline panels

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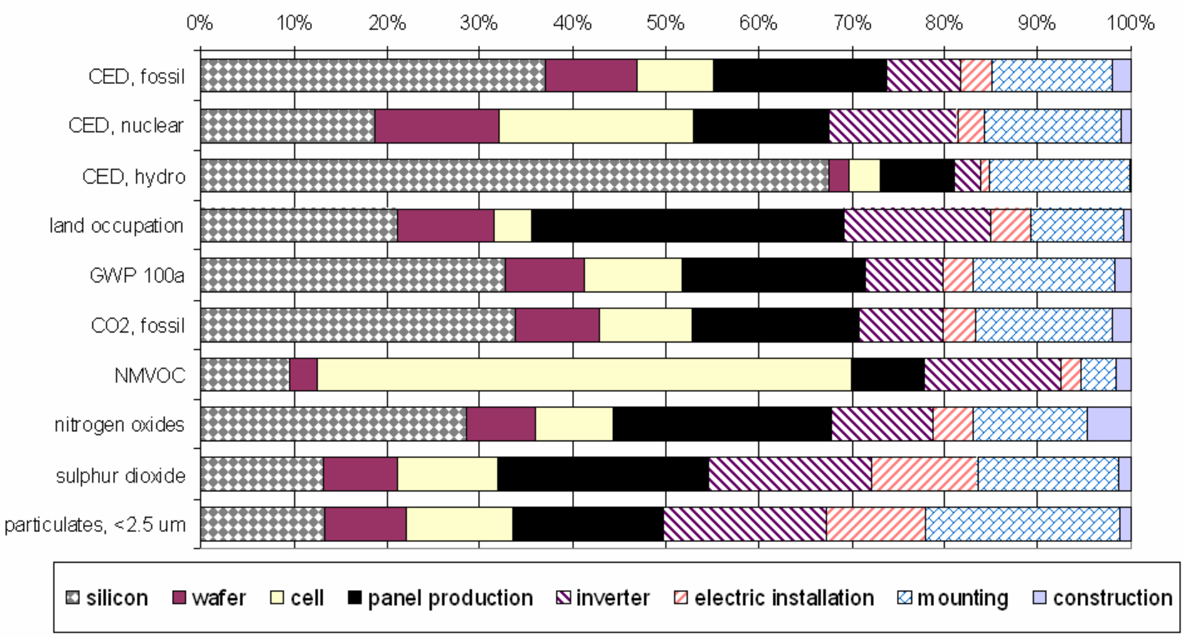

➢ **Mounting systems and inverter getting more important because of improvements in panel production process**

Cumulative energy demand of technologies

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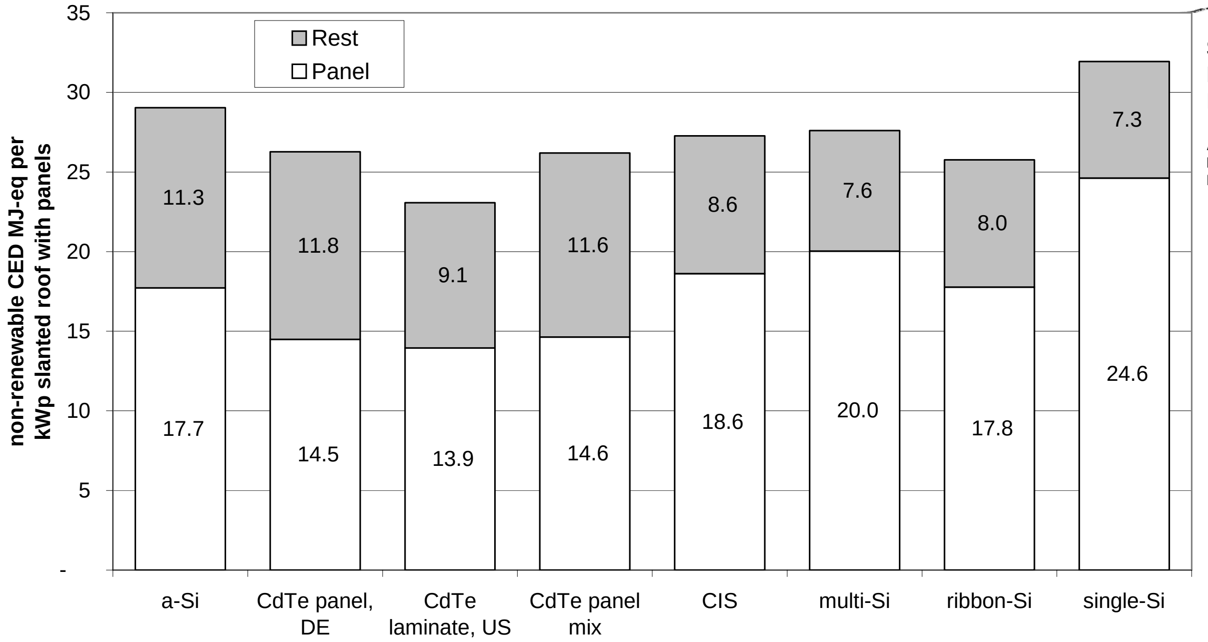

- Less efficient technologies can have lower CED for the panel, but higher for the mounting system

Development of energetic performance in Swiss LCA studies

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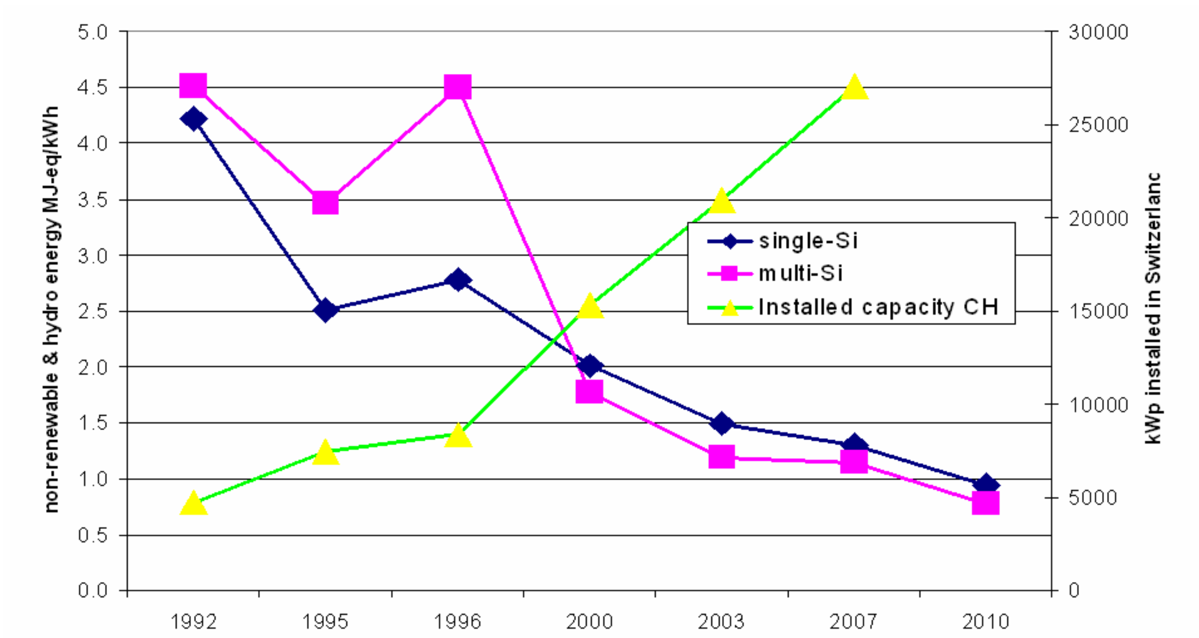
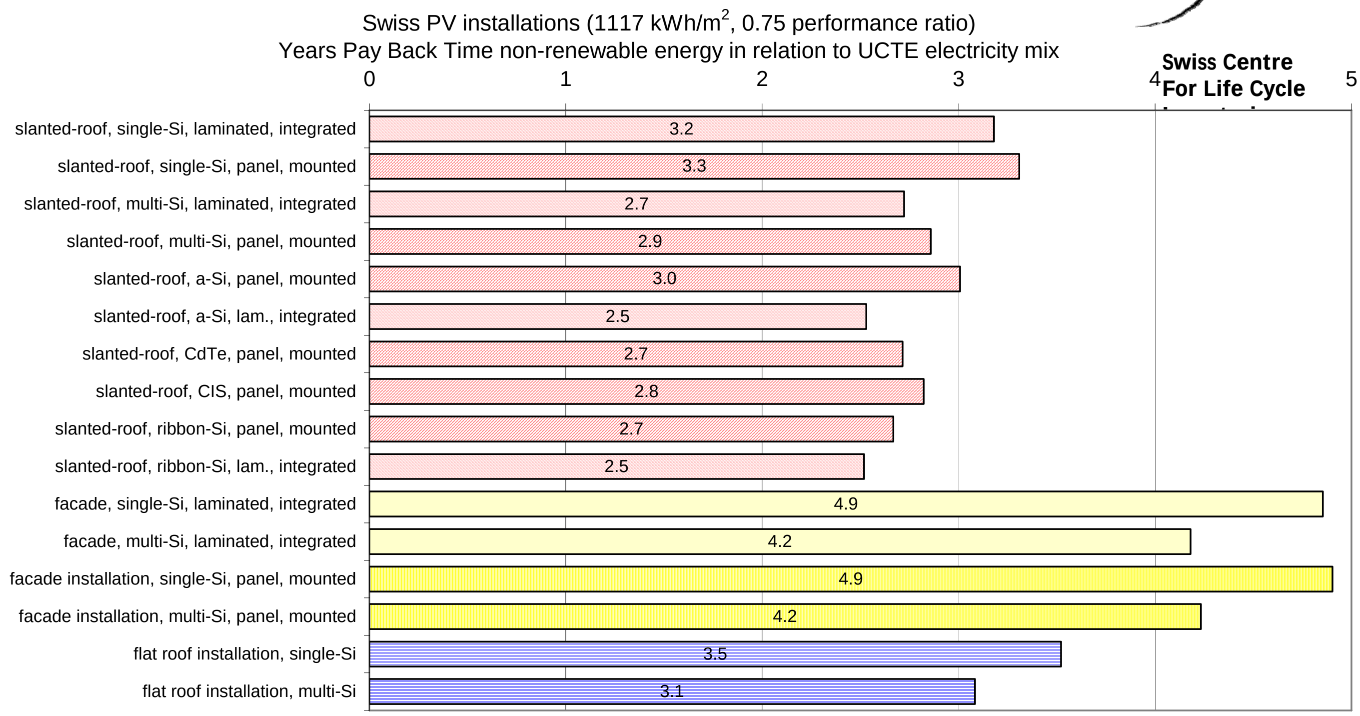


- **More detailed LCA investigation of BOS partly outweigh improvements during production**
- **Data provided for the year were they are published. Data for 2010 forecasted in 2003**

Pay Back Time Non-Renewable Energy



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➢ **Pay-back times are between 2.5 and 5 years for PV operated today in Switzerland**

Country specific photovoltaics electricity mixes

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		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**
Germany	DE	972	809	561	83%	58%	**744**	**516**
Italy	IT	1'251	1'032	676	82%	54%	**949**	**622**
Japan	JP	1'168	955	631	82%	54%	**878**	**580**
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 States	US	1'816	1'512	913	83%	50%	**1'390**	**839**

➢ PV electricity production in different countries use a calculated yield considering irradiation and average performance of PV plants compared to optimum installations

Energy pay-back time by region

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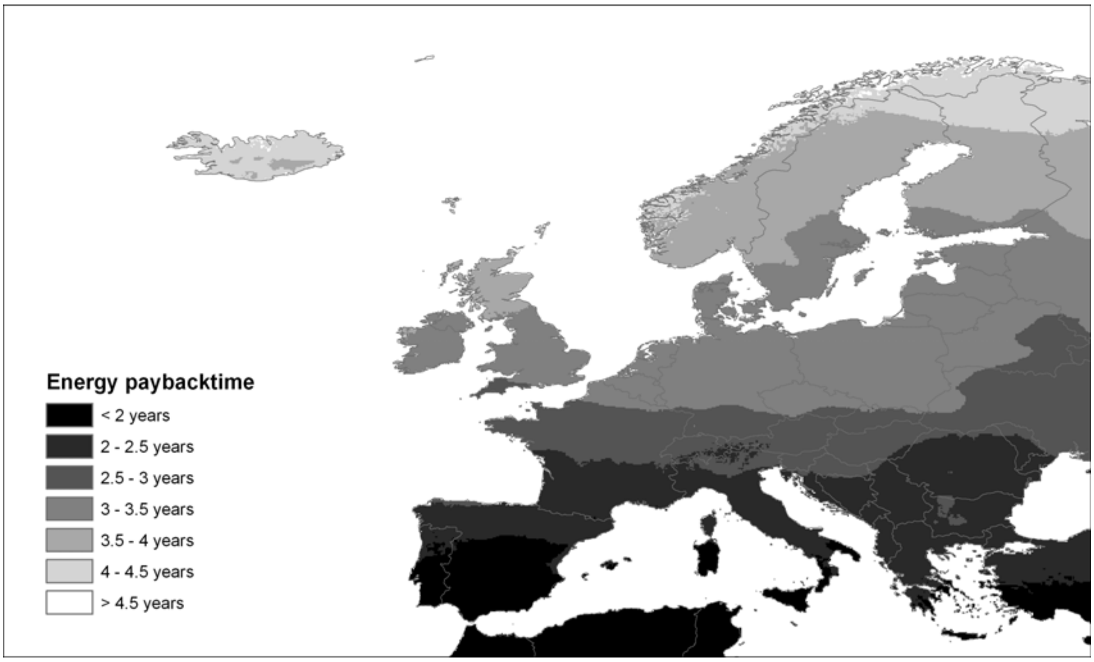

slanted-roof multicrystalline panels operated in Europe in relation to the UCTE electricity mix

GWP mitigation potential

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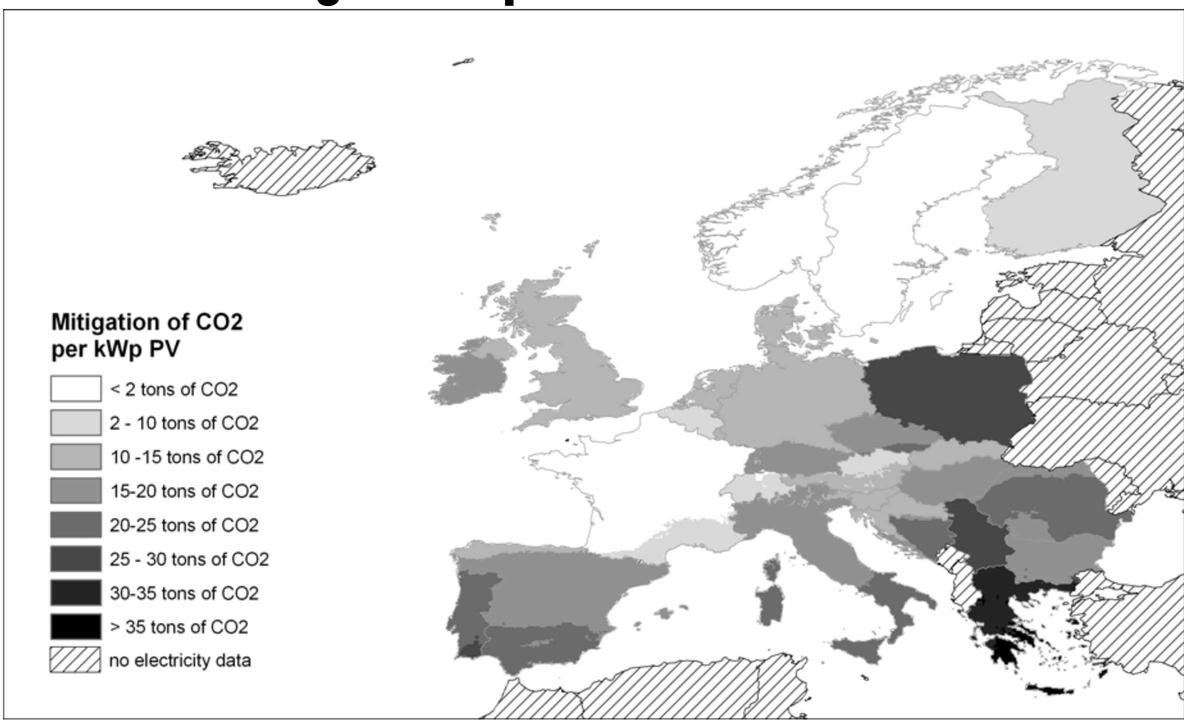

slanted-roof multicrystalline panels in relation to the country specific electricity supply mixes

Nuclear waste mitigation potential

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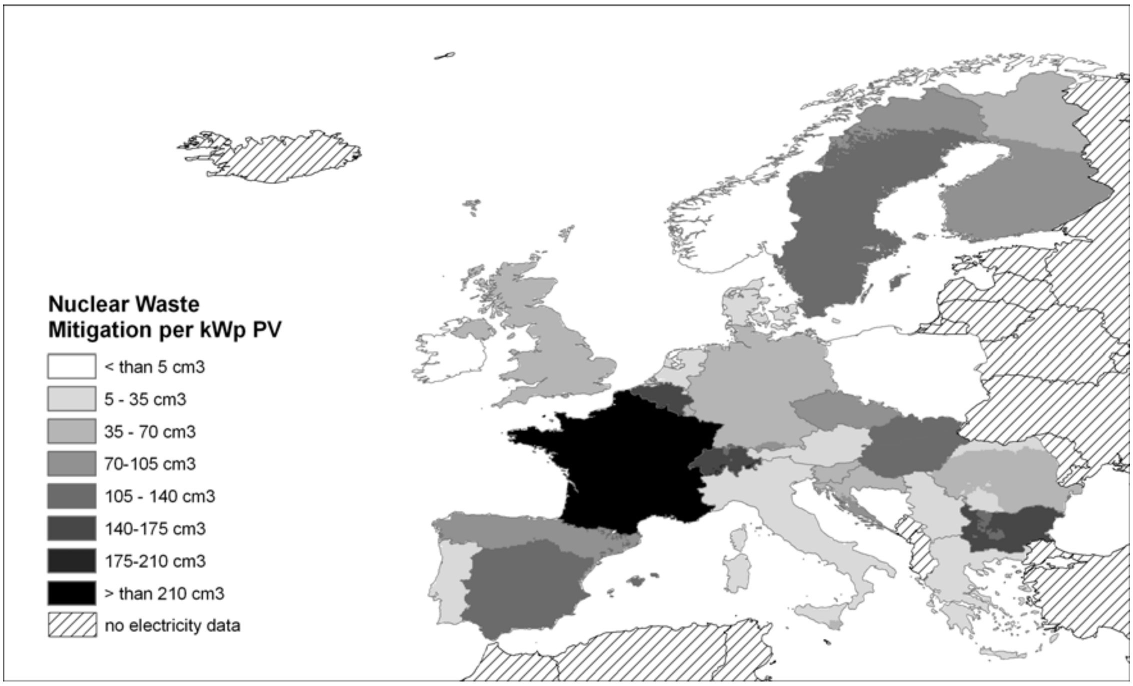

slanted-roof multicrystalline panels in relation to the country specific electricity supply mixes

Future challenges for data updates

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- Update of CdTe data due to market development
- Better investigation of variation for mounting structures
- Further country specific differences in production patterns should be taken into account
- Speciality chemicals and infrastructure for production should be investigated in more detail
- Development for end of life treatment should be observed
- New types of photovoltaics, e.g. dye-sensitized should be included
- Refinements shall concentrate on key parameters relevant in LCIA

Conclusions

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- Rapid development makes it necessary to use only most recent data
- All major types of PV technologies are investigated in a consistent and transparent way
- Discussion of company data, literature data and own models
- Energy analyses or Carbon footprints do only show a part of the environmental assessment. Process specific emissions are also important

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MG-silicon

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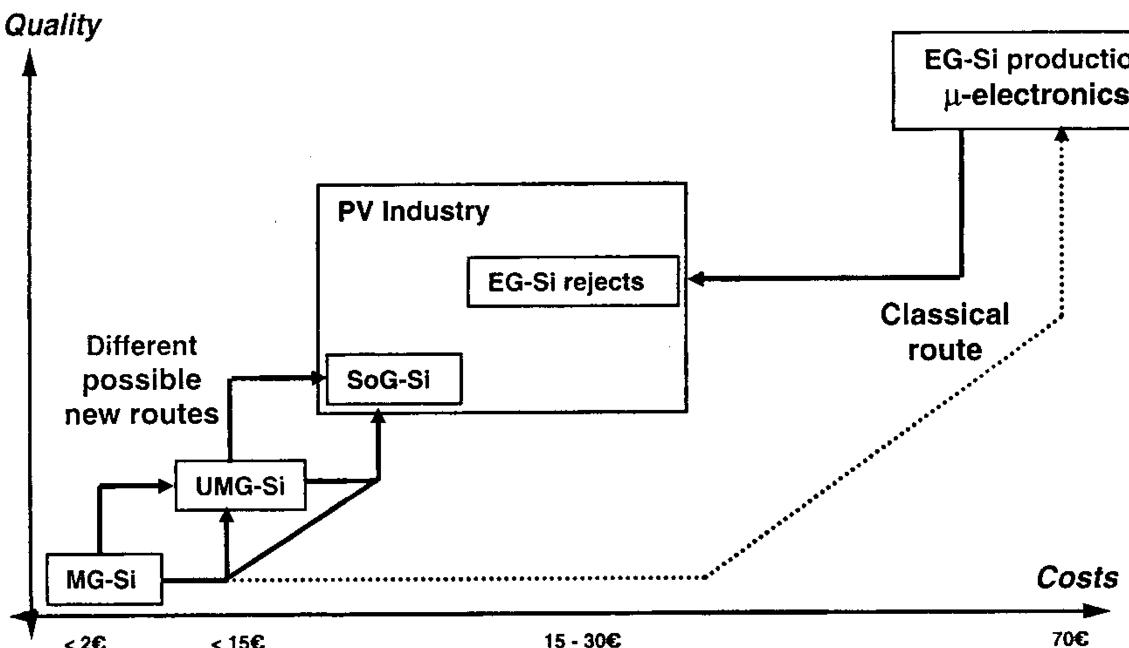
- Main producer located in Norway: electricity mix of Norway (hydro power)
- Other European silicon producers in France (nuclear power) not considered

➢ Use of charcoal from rainforest might be an important issue

EG-silicon production routes and prices



Different possibilities for production of pc-silicon for the photovoltaic industry and price per kg (Sarti & Einhaus 2002)

One process - Three products

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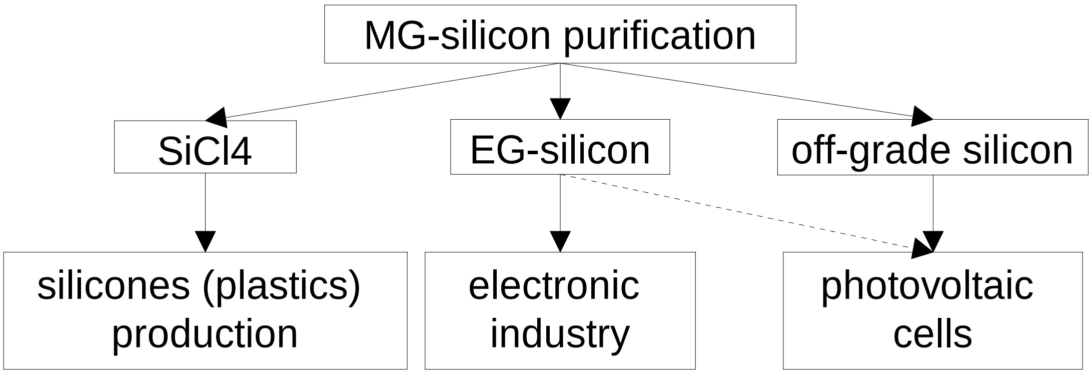

➢ Simplification to assume all off-grade silicon coming directly from EG-silicon purification

Example: inventory for allocated products

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	Name	Location	Unit	MG-silicon, to purification	silicon, electronic grade, at plant	silicon, electronic grade, off-grade, at plant	silicon tetrachloride, at plant	Allocation criteria
	Location			DE	DE	DE	DE	
	Unit			kg	kg	kg	kg	
allocated products	silicon, electronic grade, at plant	DE	kg	6.76E-1	100	0	0	
	silicon, electronic grade, off-grade, at plant	DE	kg	8.44E-2	0	100	0	
	silicon tetrachloride, at plant	DE	kg	1.20E+0	0	0	100	
technosphere	MG-silicon, at plant	NO	kg	1.00E+0	71.1	8.9	20.0	Material balance
	polyethylene, HDPE, granulate, at plant	RER	kg	6.37E-4	72.0	2.4	25.6	Revenue all products
	hydrochloric acid, 30% in H2O, at plant	RER	kg	2.00E+0	48.4	1.6	50.0	Stoechometric calculation
	natural gas, burned in boiler condensing modulating >100kW	RER	MJ	1.22E+2	96.8	3.2	-	Revenue purified silicon
	electricity, natural gas, at combined cycle plant, best	RER	kWh	8.66E+1	96.8	3.2	-	Revenue purified silicon
	electricity, hydropower, at run-of-river power plant	RER	kWh	2.74E+1	96.8	3.2	-	Revenue purified silicon
	price	GLO	€	70.36	75.00	20.00	15.00	
	revenue	GLO	€	70.36	50.67	1.69	18.00	

	Name	Location	Unit	MG-silicon, to purification	silicon, electronic grade, at plant	silicon, electronic grade, off-grade, at plant	silicon tetrachloride, at plant	
	Unit	0	0	kg	kg	kg	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		1.1	1.1	0.2	Material balance
	polyethylene, HDPE, granulate, at plant	RER	kg		6.79E-4	1.81E-4	1.36E-4	Revenue all products
	hydrochloric acid, 30% in H2O, at plant	RER	kg		1.4	0.4	0.8	Stoechometric calculation
	natural gas, burned in boiler condensing modulating >100kW	RER	MJ		174.2	46.5	-	Revenue purified silicon
	electricity, natural gas, at combined cycle plant, best	RER	kWh		124.1	33.1	-	Revenue purified silicon
	electricity, hydropower, at run-of-river power plant	RER	kWh		39.2	10.5	-	Revenue purified silicon

➢ Elementary Flow times allocation factor divided through output equals the single inventory

Consumption of purified silicon per Wp
(SoG-Si, Off-grade-Si, EG-Si)

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	single-Si 2000	multi-Si 2000	single-Si 2005	multi-Si 2005	ribbon-Si 2005
g	11.0	12.3	8.0	9.6	6.8

- Estimation of silicon losses in the several life cycle stages is a critical issue
- Silicon consumption was verified with Top-Down data for MG-silicon use per kWp

Key parameters

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	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

Silicon PV efficiency

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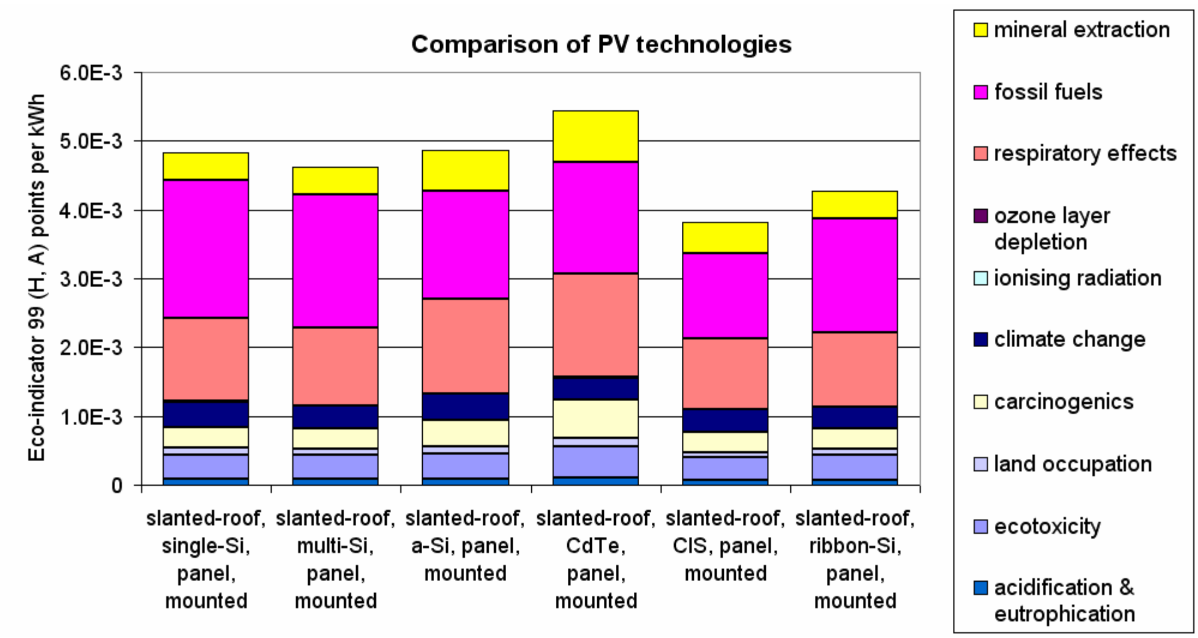
	Unit	single-Si 2003 unit	multi-Si 2003 unit	single-Si 2007 m2	multi-Si 2007 m2	ribbon-Si 2007 m2
yield, MG-Si to SoG-Si	%	95%	95%	*88%*	*88%*	*88%*
yield, SoG-Si to mc-/sc- silicon	%	*65%*	67%	*93%*	*88%*	*88%*
wafer thickness	µm	300	300	270	240	250
kerf loss (calculated for 2007 including other losses)	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				

➤ Verified with Top-Down data for MG-silicon use per kWp

Comparison of PV technologies applied in Switzerland using Eco-indicator 99 (H,A)



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Comparison of PV with other types of power plants and selected electricity mixes

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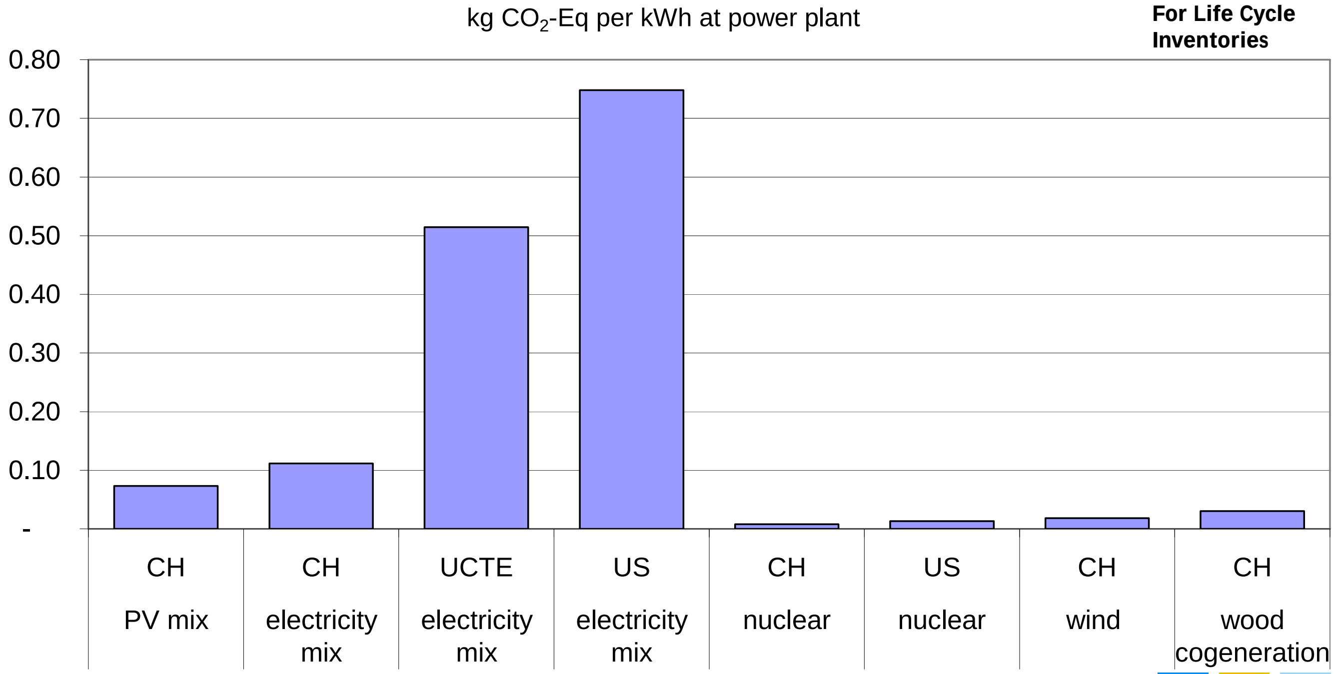

Publications

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- Jungbluth N. (2007) Photovoltaics. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.org.
- Jungbluth N., Bauer C., Dones R. and Frischknecht R. (2004) Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power. *In: Int J LCA*, **10**(1), retrieved from: http://dx.doi.org/10.1065/lca2004.11.181.3 or www.esu-services.ch .
- Jungbluth N. (2005) Life Cycle Assessment for Crystalline Photovoltaics in the Swiss ecoinvent Database. *In: Prog. Photovolt. Res. Appl.*, **2005**(13), retrieved from: www.esu-services.ch or http://www3.interscience.wiley.com/cgi-bin/jtoc/5860