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Bacelona

LCI for Photovoltaics in ecoinvent

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Overview

- System boundaries
- Inventories and Up-dates
- Allocation example
- Interpretation of results
  - Cumulative life cycle inventory
  - Uncertainties
  - LCIA

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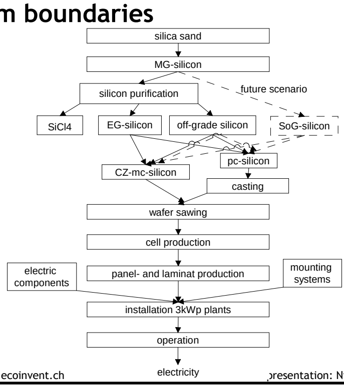
System boundaries



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Analysed 3kWp plants

Installation	Cell type	Panel type
Slope roof	mc-Si	Panel [1]
	pc-Si	Panel
	mc-Si	Laminate [2]
	pc-Si	Laminate
	mc-Si, future	Laminate [2]
	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

[1]): Panel = mounted on the roof
[2]): Laminate = integrated in the roof construction

➤ Life cycle inventory from cradle to grave for plants operated in Switzerland

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Future scenario for 2005-2010

- Present technology is still under development
- Goal: Evaluation of the potential for future PV applications
- Production of purified solar-grade silicon in a specific process
- Reduction of energy consumption in different stages based on observed minimum figures from literature
- Better efficiency of solar cells
  - pc-Si = 15.7%, mc-Si = 17.5%

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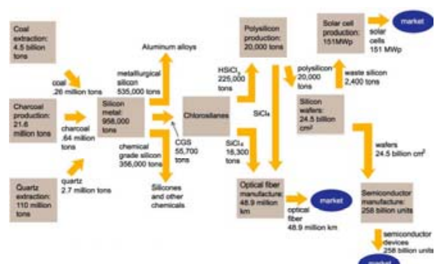
Silicon: A global market



➤ Silicon used for PV is not important for the total silicon market

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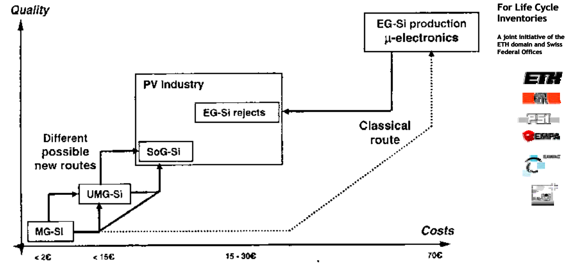
MG-silicon

- Assumption of electricity mix for Norway (hydro power)
- Other producers in France (nuclear power) not considered

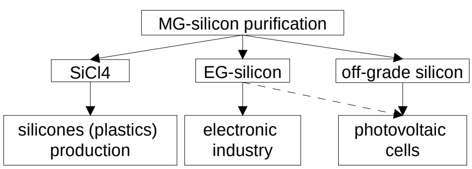
➢ Use of charcoal from rainforest might be an important issue for further investigation

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



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

Example: inventory for allocated products

	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

Example for uncertainty information

Name	Location	InfrastructureProcess	Unit	MG-silicon, to purification	UncertaintyType	StandardDeviation95%	GeneralComment
Location				DE			
InfrastructureProcess				0			
Unit				kg			
Water, cooling, unspecified natural origin	-	-	m3	4.35E+1	1	1.33	(4,4,2,3,1,5); Literature 1997
MG-silicon, at plant	NO	0	kg	1.00E+0	1	1.24	(3,1,2,1,1,5); Literature 1997
polyethylene, HDPE, granulate, at plant	RER	0	kg	6.37E-4	1	1.65	(4,4,3,3,4,5); Literature, Hagedorn, different plastics
hydrochloric acid, 30% in H2O, at plant	RER	0	kg	2.00E+0	1	1.11	(3,na,1,1,1,na); Estimation
hydrogen, liquid, at plant	RER	0	kg	6.26E-2	1	1.33	(4,4,2,3,1,5); Literature 1997

- Lognormal distribution, information for the square of standard deviation
- Pedigree matrix (reliability, completeness, Temporal correlation, geographical cor., technol. cor., Sample size) with levels from 1 to 5
- Basic Uncertainty depending on the type of input or output
- General comment for each flow

Silicon purification

- Allocation with 100% rule considering all products of the process
- Plant specific electricity mix for EG-silicon (largest European plant in Germany)
- Update for the most important process parameters (energy use)
- Analysis of process specific emissions and infrastructure

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

➢ High dynamic in the silicon market not driven by PV

➢ SoG-silicon discussed for 20 years but still not realized

➢ Forecasts for energy use turned out to be to optimistic

CZ-silicon, casting, wafer- and cell production

- Update for silicon yields
- Analysis of further process specific emissions with data from environmental reports and literature
- 50% EG-silicon and 50% Off-grade silicon as input in 2000
- 50% Solar-grade-silicon and 50% Off-grade silicon in future
- CZ-silicon investigated with data from German producer for IT-products and literature data

➢ EG-silicon is used today because of IT-sector crisis
➢ Still data gaps due to little information from industry and uncertain data

Cell efficiencies

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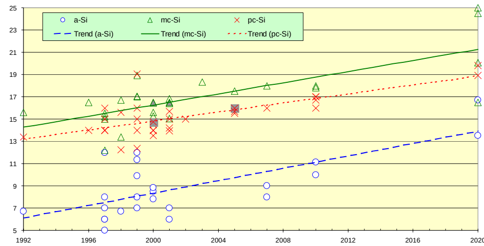

➢ Updated cell efficiency: pc-Si = 14.8%, mc-Si = 16.5%
➢ Forecasts tend to overestimate future improvements

Module- and plant production, operation for electricity production

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- Considering today sizes of cells and modules
- Only punctual update of old inventories for manufacturing

- Present yield of power plants operated in Switzerland
  - 819 kWh/kWp for production average
  - 885 kWh/kWp for flat roof and 626 kWh/kWp for facade
- Calculation of photovoltaic supply mix for Switzerland

➢ Actual yields shall be taken into account

Results of inventory analysis (Example)

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	Name Location Unit Infrastructure	Unit	electricity, photovoltaic, at 3kWp slanted-roof , mc-Si, panel, mounted CH kWh 0	MinValue	MaxValue	electricity, photovoltaic, at 3kWp slanted-roof , pc-Si, panel, mounted CH kWh 0	MinValue	MaxValue
Particulates, < 2.5 um	high population density	kg	2.0E-6	1.1E-6	3.6E-6	1.7E-6	1.1E-6	2.6E-6
Particulates, < 2.5 um	low population density	kg	**1.5E-5**	8.2E-6	2.7E-5	**1.3E-5**	8.1E-6	2.1E-5
Particulates, < 2.5 um	lower stratosphere + upper troposphere	kg	7.5E-16	3.0E-16	1.6E-15	5.9E-16	2.4E-16	1.2E-15
Particulates, < 2.5 um	unspecified	kg	5.0E-6	1.6E-6	1.2E-5	5.0E-6	1.4E-6	1.2E-5
Particulates, < 2.5 um	total	kg	2.2E-5			2.0E-5		

➢ About 1000 Elementary Flows in the inventory analysis
➢ Division in SubCategories

Inventory of PV electricity: Contribution analysis

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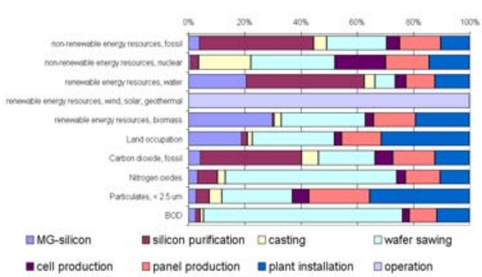

➢ Many process specific impacts and flows

LCIA of PV electricity: Contribution analysis

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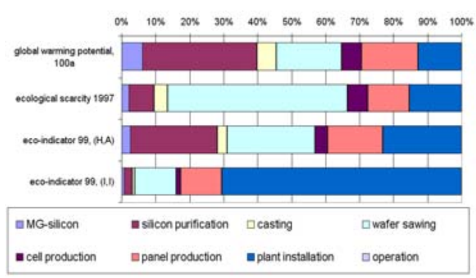

➢ Copper use is quite important for an assessment with EI'99 (I,I)

Comparison of PV technologies with Eco-indicator 99 (H,A)

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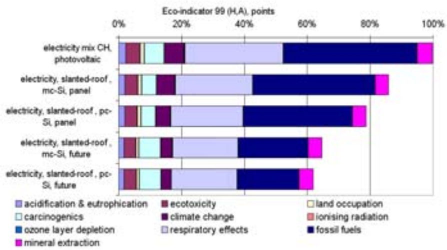
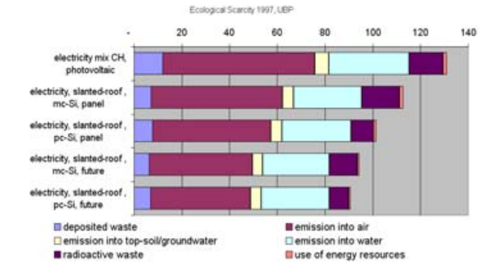


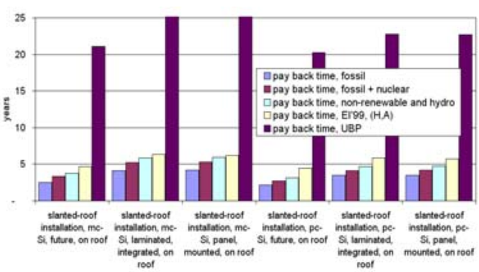
- Respiratory Effects: Particle- und NOx-emissions
- Fossil Fuels: Gas and oil consumption

Comparison of PV technologies with ecological scarcity method



- NOx and nitrate from wafer production are important

Pay Back Time



- Pay back time depends on reference system and LCIA method

Key parameter

	unit	mc-Si	pc-Si	mc-Si future	pc-Si future
MG-silicon production					
electricity use, NO 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	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	Wp	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
3kWp-plant					
panel area	$m^2/3kW_p$	18.2	20.3	17.1	19.1
operation					
yield, slope-roof	kWh/kW_p	885	885	885	885
yield, facade	kWh/kW_p	626	626		
yield, CH electricity mix	kWh/kW_p	819	819		

Silicon efficiency

	Unit	mc-Si Stk	pc-Si Stk	mc-Si, optimiert Stk	pc-Si, optimiert Stk
Spezifisches Gewicht Silizium	g/cm3	**2.33**			
Ausbeute Zellenherstellung	%	*95%*	*92%*	*95%*	*92%*
Waferdicke	µm	300	300	300	300
Sägespalt	µm	200	200	200	200
Wafergrösse	cm^2	100	100	100	100
Wafergewicht	g	6.99	6.99	6.99	6.99
Sägeverluste Wafer	g	4.66	4.66	4.66	4.66
Sägeverluste	%	*60%*	*60%*	*60%*	*60%*
Davon Recycling	%	*10%*	*10%*	*50%*	*50%*
Summe Si direkt für Wafer	g	11.18	11.18	9.32	9.32
Ausbeute pc-Silizium Blockgiessen	%	-	67%	-	*70%*
Ausbeute pc-Silizium zu CZ-mc-Silizium	%	*65%*	-	*75%*	-
Bedarf gereinigtes Silizium pro Zelle	**g**	**18.1**	**18.2**	**13.0**	**14.5**
Bedarf gereinigtes Silizium pro Wp	**g**	**11.0**	**12.3**	**7.5**	**9.2**
Ausbeute MG-Silizium zu gereinigtem Silizium	%	95%	95%	*80%*	*80%*
Bedarf MG-Silizium pro Zelle	**g**	**19.0**	**19.2**	**16.3**	**18.1**
Gesamteffizienz MG-Si zu Wafer	*%*	*36.8%*	*36.5%*	*42.9%*	*38.5%*

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

Conclusions for ecoinvent PV inventory

- Extended reworking and update of life cycle inventories for the year 2000 European production processes that can be considered for plants in Switzerland
- Estimation for possible future improvements until 2010
- Consideration of a range of process specific emissions
- Basis for the evaluation of photovoltaic and comparison with other types of electricity production
- Validity for other countries:
  - Consideration of country or plant specific yields
  - Adaptation of energy models in the process chain for production sites outside Europe

Shortcomings

- Most elementary flows are based on only one information source
- If several sources are available they show a large variation
- Data are mixed from different sources and different time periods

- Refinements shall be concentrated on key parameters for LCIA

Outlook

- Forecasts tended to underestimate the environmental impacts
- Real market situation (raw material supply, electricity, etc.) must be considered
- Process specific emissions are important for the LCIA. Energy analysis or CO2-emissions are not sufficient for an environmental assessment
- The cooperation with PV industry (silicon purification, cell production) must be improved. Today it is low in comparison with other sectors

Publications

- Jungbluth N. (2003) Photovoltaik. 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.ch.
- 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), pp., 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), pp. 1-18, retrieved from: www.esu-services.ch or http://www3.interscience.wiley.com/cgi-bin/jtoc/5860