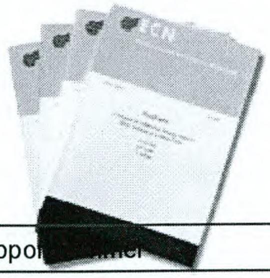


Begeleidingsformulier ECN-Publicatie

Algemene gegevens

Rapportnummer	ECN-E--06-019		
Unit/stafafdeling	ZON	Organisatorische eenheid	Si PV
Projectleider		Clusternummer	
Contactpersoon	brak	Telefoon	4761
Titel	Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production - Excel File		
-			
-			
Auteur 1	Wild - Scholten, M.J. de	Auteur 4	
Auteur 2	Alsema, E.A.	Auteur 5	
Auteur 3		Auteur 6	
Opmerking			
Projectfinanciering	[ ] Basis	[ ] ENGINE	[ ] Derden/Samenwerking

Beoordeling door Reviewers

nr	Naam	Beoordeling (zie eventueel document)	Ontvangen	Verzonden	Paraaf
1	T. Veltkamp	akkoord	31/8/06		
2					
3					
4					

Beoordeling door Groepsleider

Naam:	ja	nee	Te nemen actie		
Mening opdrachtgever gevraagd?	[ ]	[x]	N.V.T.		
Geschikt voor publicatie in tijdschrift?	[ ]	[x]			
Geschikt voor persbericht?	[x]	[ ]			
Akkoord met resultaat?	[x]	Datum	31/8/06	Paraaf	
Commentaar					

Beoordeling door Unit Manager (of gedelegeerde)

Naam:	ja	nee	Te nemen actie
Relevantie openbare meningsvorming?	[ ]	[ ]	
Octrooi-aspecten?	[ ]	[ ]	

Vrijgave

Accordering voor productie/vrijgave	Datum	Paraaf hoofdauteur	Datum	Paraaf UM
-			31/8/06	
Distributie	Opdrachtgever	Unit	Overig	Totaal
Aantal				
Verrekening productiekosten op				

Opmerkingen

Title:
Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production

Version:
Publication date:

Authors

M.J. de Wild-Scholten, Energy research Center of the Netherlands, Petten, The Netherlands

E.A. Alsema, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, The Netherlands

Reference

If you use these data for (scientific) publication we would appreciate that you include the following reference:

M.J. de Wild-Scholten, E.A. Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production, Proceedings of the Materials Research Society Fall 2005 Meeting, Symposium G, Boston, USA, 28-30 November 2005, online publication at: www.mrs.org

M.J. de Wild-Scholten, E.A. Alsema, E.W. ter Horst, M. Bächler, V.M. Fthenakis, A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems, 21th European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006

Updates:

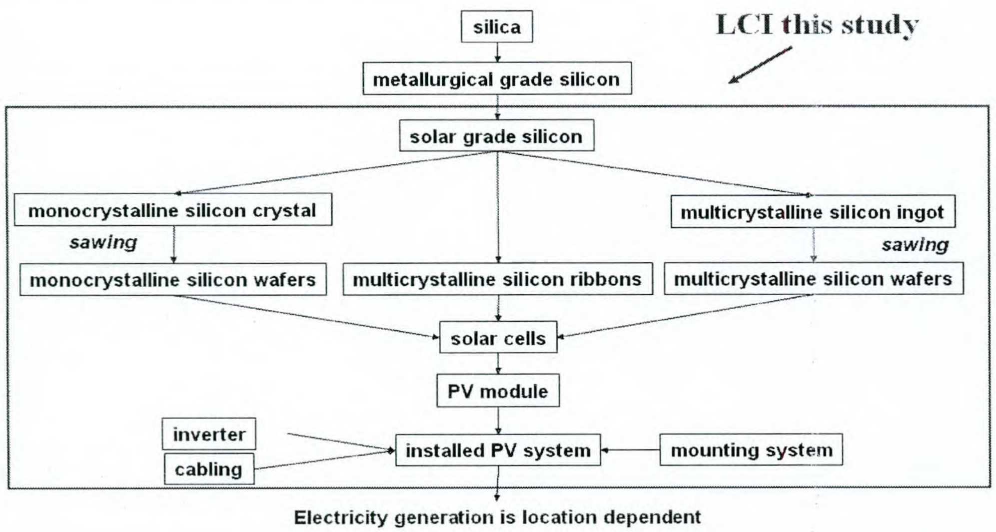
More information on the collection and preparation of these data, as well as updates of the dataset can be found at:

Acknowledgements:

The set of Environmental Life Cycle Inventory data of PV modules was collected by Mariska De Wild and Erik Alsema, in the framework of the CrystalClear research project. The CrystalClear project was funded by the European Commission under contract nr. SES6-CT_2003-502583. More information on this project can found at:

The set of Environmental Life Cycle Inventory data of Balance-of-System components was collected by Mariska De Wild and Erik Alsema. Part of this work was carried out in the project "Technologie- en Milieuverkenningen" with ECN project number 7.4750 financed by the Ministry of Economic Affairs, the Netherlands

Scope:
The following picture explains the scope of the data set:



Notes:
Input of **dissolved chemicals** follows convention applied in Ecoinvent database: Input and output data for chemicals production refer to its active substance, but the carrier substance is stated in the name and considered as an input in the inventory. Thus the inventory for 1 kg "sodium hydroxide, 50% in H_2O, production mix, at plant" refers to the production of 2 kg NaOH with a water content of 50%. (i.e., 1 kg pure NaOH plus 1 kg pure H_2O)!!!

Disclaimer:

The authors have assembled this LCI data set to the best of their knowledge and in their opinion it gives a reliable representation of the crystalline silicon module production technology in Western-Europe in the year 2004 and Balance-of-System components of the year 2006. However, most of the data were provided to us by the companies that helped us. Although we have cross-checked the data from different sources we cannot garuantee that it does not contain any errors. Therefore we cannot accept any responsability for the use of these data.

1,1
01 september 2006

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http://www.mrs.org/

http://www.photovoltaic-conference.com/

http://www.ecn.nl/publicaties/default.aspx?au=43

http://www.ipcrystalclear.info

Name	**High purity polycrystalline silicon, feedstock material for crystalline silicon ingots (Poly-Si)**
Time period	2004
Geography	Europe, Western and North America
Technology	Mixed data
Representativeness	Average of data from one company and estimated data from another company based on literature data
Version	1.2
Date	15-12-2005
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Collection method	Data collection by factory representative + literature data
Data treatment	
Comment	Production with Siemens process either from $SiHCl_3$ or SiH_4. Partly with standard Siemens process and partly with modified Siemens ("solar grade") at reduced electricity consumption. Mix of electricity supply in accordance with actual conditions at considered production locations.
Allocation rules	NA

Products	Unit	Value	Comment
Polycrystalline silicon, Siemens process	kg	1,00	high purity, with specifications applicable for photovoltaic industry
Materials			
MG-silicon	kg	1,13	metallurgical grade silicon
Inorganic chemicals, unspecified	kg	2,00	mix of NaOH, HCl and H_2
Heat from natural gas	MJ	185	for process heat
Electricity/heat			
Electricity, from combined cycle plant, gas-fired	kWh	45	actual sources of electricity can vary with considered production location
Electricity, hydropower	kWh	65	mix of reservoir and run-of-river hydro
Emissions to air			
			N.B.: emissions from natural gas combustion not included here yet!

Version history

1,2	Documentation changed.
1,1	Format of cells changed

Name	**mono-crystalline silicon wafer from poly-Si**
Time period	2004
Geography	North America + Europe, Western + Asia, former USSR
Technology	Mixed data
Representativeness	Estimated data, partly based on data from one company (but with many unclarities) supplemented with literature sources and many own estimates.
Version	1.2
Date	2-1-2006
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Collection method	
Data treatment	Averaging over 3 different assumed production locations
Comment	Includes both Czochralski crystal pulling and wafer cutting processes. Wafer thickness 300 um. The process for internal recycling of silicon is NOT included in the process data, external recyling of sawing slurry is not accounted either. The amount of poly-silicon includes virgin AND recycled silicon.
Allocation rules	NA

Products	**Unit**	**Amount**	**Comment**
mono-Si wafer	m^2	1,00	typical wafer: 125x125 mm^2 (0.0156 m^2), semisquare, thickness 300 um
Materials			
SOLIDS			
poly-Si	kg	1,58	polycrystalline silicon of semiconductor or solar grade quality, partly internally recycled silicon from ingot cut-offs and broken wafers
quartz crucible	kg	0,36	for melting the silicon
glass	kg	0,01	for temporarily attachment of bricks to wiresawing equipment, assumed same as multi wafers
steel wire	kg	1,49	for wafer cutting, assumed same as multi wafers
silicon carbide (SiC)	kg	2,61	for sawing slurry, assumed same as multi wafers
GASES			
argon (Ar)	kg	6,20	for crystal growing
LIQUIDS			
polyethylene glycol (PEG)	kg	2,63	for sawing slurry, assumed same as multi wafers
dipropylene glycol monomethyl ether (DPM)	kg	0,30	for wafer cleaning
adhesive	kg	0,002	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	0,24	for wafer cleaning
Sodium hydroxide, 50% in H_2O	kg	0,015	see note 1, for wafer cleaning, assumed same as multi wafers
Hydrochloric acid, 30% in H_2O	kg	0,0027	see note 1, for wafer cleaning, assumed same as multi wafers
Acetic acid, 98% in H_2O	kg	0,039	see note 1, for wafer cleaning, assumed same as multi wafers
tap water	kg	0,006	for ingot sawing
water, deionised	kg	65	for wafer cleaning

Electricity/fuel			
electricity, medium voltage	kWh	145	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	77	general use + furnaces
Final waste flows			
Silicon waste (not recycled)	kg	0,4	unused part of crystal, estimate
Waste to treatment			
cutting waste (Si + slurry)	kg	6,0	not recycled internally, but SiC and cutting fluids may be partially recovered at specialized facility

Version history

1,2	Product multi-Si wafer changed to mono-Si wafer.
1,1	Documentation changed.
1,0	Format changed
0,9	Steel wire consumption updated

Name	**multi-silicon wafer from poly-Si**
Time period	2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 3 companies, total production 1.5E6 m^2 wafer area.
Version	1.5
Date	15-12-2005
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Collection method	Data collection by factory representatives
Data treatment	
Comment	Includes both the ingot growth and wafer cutting processes. Average wafer thickness 285 um. The process for internal recycling of silicon is NOT included in the process data, external recyling of sawing slurry is not accounted either. The amount of poly-silicon includes virgin AND recycled silicon.
Allocation rules	NA

Products	**Unit**	**Amount**	**Comment**
multi-Si wafer	m^2	1,00	typical wafer area: 125x125 mm^2 (0.0156 m^2), average thickness 285 um
Materials			
SOLIDS			
poly-Si	kg	1,67	polycrystalline silicon of semiconductor or solar grade quality, partly internally recycled silicon from ingot cut-offs and broken wafers
quartz crucible	kg	0,39	for ingot growing
glass	kg	0,01	for temporarily attachment of bricks to wiresawing equipment
steel wire	kg	1,49	for wafer cutting
silicon carbide (SiC)	kg	2,61	for sawing slurry
GASES			
nitrogen (N_2)	kg	0,05	for ingot growing
argon (Ar)	kg	0,30	for ingot growing
helium (He)	kg	1,362E-04	for ingot growing
LIQUIDS			
polyethylene glycol (PEG)	kg	2,63	for sawing slurry
dipropylene glycol monomethyl ether (DPM)	kg	0,30	for wafer cleaning
adhesive	kg	0,002	for temporarily attachment of bricks to wire-sawing equipment
tenside (concentrated)	kg	0,24	for wafer cleaning
Sodium hydroxide, 50% in H_2O	kg	0,01	see note 1, for wafer cleaning
Hydrochloric acid, 30% in H_2O	kg	0,0027	see note 1, for wafer cleaning
Acetic acid, 98% in H_2O	kg	0,039	see note 1, for wafer cleaning
tap water	kg	0,006	for ingot sawing
water, deionised	kg	65	for wafer cleaning

Electricity/fuel			
electricity, medium voltage	kWh	30	total electricity consumption including direct and indirect process energy and overhead energy
natural gas	MJ	4	for removing adhesive after sawing
Final waste flows			
silicon waste (not recycled)	kg	0,3	unused part from ingot, estimate
Waste to treatment			
cutting waste (Si + slurry)	kg	6,2	not recycled internally, but SiC and cutting fluids may be partially recovered at specialized facility

Version history

1,5	Format amount changed from scientific to number
1,4	Documentation changed.
1,3	Format changed
1,2	Steel wire consumption updated with extra data source
1,1	Waste amounts corrected, internally recycled silicon is accounted in Si input, therefore no recyclable silicon output

Name	**ribbon silicon wafer from poly-Si**
Time period	2004
Geography	Europe, Western + North America
Technology	Average technology
Representativeness	Average from 3 specific processes of which one in pilot phase.
Version	1.2
Date	15-12-2005
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Collection method	Data collection by factory representatives.
Data treatment	
Comment	Wafer thickness 300-330 um. Wafer area 120-156 cm^2.
Allocation rules	NA

Products	**Unit**	**Amount**	**Comment**
ribbon Si wafer	m^2	1	
Materials/fuels			
SOLIDS			
poly-Si	kg	0,91	
graphite	kg	0,014	
GASES			
argon (Ar)	kg	4,38	
Electricity			
electricity, medium voltage, total	kWh	45,7	
Emissions to air			
argon	kg	4,38	
Waste to treatment			
graphite crucibles	kg	0,014	
wafer waste, to recycling	kg	0,09	

Version history

1,2	Documentation changed.
1,1	Format changed. Comments added

Name	**mono- or multi-crystalline silic**
Time period	2004
Geography	Europe, Western
Technology	Average technology
Representativeness	Average from 5 specific processe
Version	1.2
Date	15-12-2005
Record	Erik Alsema (Utrecht University),
Generator	Mariska de Wild (ECN), Erik Alse
Collection method	Data collection by factory represe
Data treatment	Some inputs and emissions aggr
Comment	Wafer thickness 270-300 um.
Allocation rules	NA

Products	**Unit**	**Amount**
multi- or mono-Si cell (156 cm^2)	p	1,00
Resources		
Water, cooling	m^3	1,56E-02
Materials/fuels		
SOLIDS		
multi/mono-Si wafer (156 cm^2)	p	1,06E+00
phosphorus paste	kg	2,27E-05
metallisation paste	kg	1,17E-03
polystyrene, expandable	kg	6,36E-06
GASES		
nitrogen (N_2)	kg	2,89E-02
oxygen (O_2)	kg	1,59E-03
argon (Ar)	kg	4,01E-04
Fluorinated compound mix (CF_4, C_2F_6, SF_6, NF_3)	kg	4,93E-05
ammoniak (NH_3)	kg	1,05E-04
silane (SiH_4)	kg	1,89E-05
LIQUIDS		
sodium hydroxide, 50% in H_2O (NaOH)	kg	2,45E-03
acetic acid, 98% in H_2O (CH_3COOH)	kg	4,42E-05
hydrochloric acid, 30% in H_2O (HCl)	kg	7,12E-04
hydrogen fluoride (HF) 100%	kg	5,89E-04
nitric acid, 50% in H_2O (HNO_3)	kg	4,17E-04
$POCl_3$ phosphoryl chloride	kg	3,39E-06
phosphoric acid, industrial grade, 85% in H_2O (H_3PO_4)	kg	1,19E-04
sodium silicate	kg	1,17E-03
calcium chloride ($CaCl_2$)	kg	3,37E-04

tetraisopropyltitanate (TPT, a titanium precursor)	liter	2,22E-08
isopropanol	kg	1,23E-03
ethanol	kg	9,98E-06
solvents, organic, unspecified	kg	2,24E-05
water, deionised	kg	2,15E+00
Electricity		
electricity, medium voltage	kWh	5,90E-01
natural gas	MJ	7,42E-02
fuel oil	liter	5,06E-04
Emissions to air		
aluminum	kg	1,21E-05
hydrogen chloride	kg	4,16E-06
hydrogen fluoride	kg	7,56E-08
lead	kg	1,21E-05
particulates, unspecified	kg	4,16E-05
silicon dioxide	kg	1,13E-06
silver	kg	1,21E-05
sodium hydroxide	kg	7,56E-07
tin	kg	1,21E-05
VOC, volatile organic compounds	kg	3,02E-03
FC-gases (CF_4, C_2F_6, SF_6, NF_3)	kg CO_2-eq	4,41E-02
Final waste flows		
Photovoltaic cell waste	kg	4,31E-03
Waste to treatment		
mono- or multi-Si cell, to recycling	p	1,76E-02
neutral solution	m^3	7,31E-01
alkaline solution	m^3	2,17E-04
acid solution	m^3	7,87E-04
organic waste	liter	1,22E-04

Version history

1,2	Documentation changed.
1,1	Format changed

on cell

ɜs and companies (4 multi + 1 mono)

Mariska de Wild (ECN)

ɜma (Utrecht University)

ɜntatives.

'egated to protect sensitive data.

Comment
cell area 156 cm^2, typical thickness 270-300 um
cooling water
+ 6% cell loss
for emitter formation
aggregated value for front and back pastes containing, silver content 1.6E-4 kg
for packaging
aggegrate value for different fluorinated source gases
for silicon nitride deposition
for silicon nitride deposition
for emitter formation
for emitter formation

for titanium dioxide antireflection coating deposition
Emission in **kg CO_2 equivalent**, estimate based on 70% source gas utilisation

Name	**Crystalline silicon PV module production**
Time period	2004
Geography	Europe, Western
Technology	Mixed data
Representativeness	Average from 2 companies + literature data
Version	1.4
Date	2-1-2006
Record	Erik Alsema (Utrecht University), Mariska de Wild (ECN)
Generator	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Collection method	Data collection by factory representatives and literature data
Data treatment	
Comment	Only materials and energy use for module lamination and further assembly. Typical total area (excluding frame) efficiencies are 14.0% for mono-Si modules, 13.2% for multi-Si modules and 11.5% for ribbon-Si modules.
Allocation rules	NA

N.B.: Module parameters may be changed below (red figures):

Number of cells, width:	**6**	
Number of cells, length:	**12**	
Cell size (length):	**12,5**	cm
Cell area factor:	**1,00**	
Cell efficiency (encapsulated)	**14,7**	%
Calculated parameters:		
Module width (w/o frame)	**80**	cm
Module lenght (w/o frame)	**156**	cm
Module area (w/o frame)	**1,25**	m^2
Module perimeter (=frame length)	**4,72**	m
Number of cells:	**72**	
Module power	**165**	Wp
Module efficiency (glass area, excl. frame)	**13,2**	%

N.B.: Material quantities below are calculated from the module parameters above

Products	**Unit**	**Amount**	**Comment**
Module, c-Si	p	1,00	dimensions see above
Materials			
Solar cells	p	73,4	+2% cell loss
Aluminium profile	kg	3,8	for frame, may vary per manufacturer
Polyphenylenoxid	kg	0,2	junction box, may vary per manufacturer
Glass sheet, low iron, tempered	kg	11,4	assuming 3.6 mm glass thickness, varies from 3.2 to 4.0 depending on application, size and manufacturer, +1% loss
Ethyl Vinyl Acetate	kg	1,3	EVA consumption 0.96 kg/m^2, +6% more than glass area

Back foil, for solar cell module	kg	0,32	50% polyvinylfluoride, 50% polyethylene terephthalate, 0.243 g/m^2 (0.17 mm thickness) 7% cutting loss
Copper	kg	0,14	copper ribbbons for cell interconnection
Tin	kg	0,007	Sn60Pb40 plating on tabbing material, Sn plating on interconnect/terminal ribbons
Lead	kg	0,004	Sn60Pb40 plating on tabbing material, some manufacturers use lead free.
Nickel	kg	0,00020	Ni plating on interconnect/terminal ribbons
Soldering flux	kg	0,0100	soldering flux, 95% propanol, no halogens
Methanol	kg	0,0162	cleaning fluid 13 ml/m^2
Silicone	kg	0,0029	for diaphragma of laminator
Silicone kit	kg	0,150	kit to attach frame and junction box
Cardboard	kg	1,37	packaging; estimation: 2 modules per cardboard box, 1 kg/m^2 board, 2.2 m^2 board per m^2 module
Tap water	kg	27	for glass rinsing and general use
Electricity			
Electricity, medium voltage	kWh	**8,3**	total process energy
Final waste flows			
Solar cells waste	kg	0,015	2% loss, 10 g per cell, may be recycled
Waste to treatment			
Solar glass, low-iron, to recycling	kg	0,11	1% breakage loss assumed
Ethylvinylacetate, foil, to waste incineration	kg	0,05	4% cutting loss
Back foil, to waste incineration	kg	0,02	7% cutting loss

Version history

1,4	Unit pc changed to p.
1,3	Comment changed: typical module efficiencies added.
1,2	Documentation changed.
1,1	Format changed.
1.0a	Correction cell/module efficiency, no effect on LCI data

Name	**mounting structure to fix the modules to a roof or to the ground**
Time period	2006
Geography	Europe, Western
Technology	Data from a specific process and company
Representativeness	Data of one company
Version	1.0
Date	1-9-2006
Record	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Generator	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Collection method	For roof top systems: 4 rows of 13 SolarWorld SW220 poly module with 6 x 10 multicrystalline cells of 156 mm x 156 mm. For ground-based systems see references below.
Data treatment	
Comment	
Allocation rules	NA

		on-roof	on-roof	in-roof	in-roof	ground	ground	
company:		Phönix Sonne	Schletter	Schletter	Schweizer	Phönix Sonne	Springerville	
type of mounting system:		TectoSun	Eco05+EcoG	Plandach5	Solrif			
framed (f) or unframed (u) modules:		f	f+u	f+u	u	f	f	
Products	**Unit**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Amount**	**Comment**
mounting structure	m2	1	1	1	1	1	1	
Materials/fuels								
SOLIDS								
steel	kg	0	0	0	0	11,5	4,01	
stainless steel	kg	0,49	0,72	0,28	0,08	0,17	0	
aluminium	kg	0,54	0,97	1,21	1,71	1,26	0	
concrete	kg	0	0	0	0	0	8,03	
EPDM	kg	0	0	1,41	1,41	0	0	EPDM underlayer, thickness 1.14 mm
avoided roof tiles	kg	0	0	40	40	0	0	ceramic roof tiles
total without EPDM/roof tiles	kg	1,03	1,69	1,49	1,79	12,93	12,04	

Version history

1,0

References

[1] M.Bächler, C.Bindel, Cost comparison of large scale crystalline and thin-film PV systems, 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain (2005) .

[2] J.E.Mason, V.M.Fthenakis, T.Hansen, H.C.Kim, Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation, Progress in Photovoltaics 14 (2006) 179.

Name	**cabling**
Time period	2006
Geography	Europe, Western
Technology	Data from a specific process and company
Representativeness	Data of one company
Version	1.0
Date	1-9-2006
Record	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Generator	Mariska de Wild (ECN), Erik Alsema (Utrecht University)
Collection method	http://www.helukabel.de/download.php?lang=en&i
Data treatment	
Comment	Helukabel Solarflex 101, 4 mm^2, ROHS compliant
Allocation rules	NA

Products	**Unit**	**Amount**	**Comment**
Cable DC 4 mm^2	m	1	
Materials/fuels			
SOLIDS			
copper	kg	0,038	Cu, Sn coated
TPE = Thermoplastic elastomere	kg	0,030	TPE
Electricity			
electricity, medium voltage, total	kWh	0,0	unknown
Emissions			unknown
Waste to treatment			unknown

Version history

1,0

	Amount	Unit	Reference	Website
Solar irradiation - Middle Europe	1000	kWh/m^2	PV-GIS	http://re.jrc.cec.eu.int/pvgis/pv/
Solar irradiation - South Europe	1700	kWh/m^2	PV-GIS	http://re.jrc.cec.eu.int/pvgis/pv/
Performance ratio	0,75	-	IEA-PVPS Task 2	http://www.iea-pvps-task2.org/