fair life cycle thinking

treeze Ltd., Kanzleistrasse 4, CH-8610 Uster, www.treeze.ch

Life cycle assessment of low power solar inverters (2.5 to 20 kW)

Authors
Laura Tschümperlin, Philippe Stolz, Rolf Frischknecht

commissioned by
Swiss Federal Office of Energy SFOE

Uster, 3 October 2016

Imprint

Title	Life cycle assessment of low power solar inverters (2.5 to 20 kW)
Authors	Laura Tschümperlin, Philippe Stolz, Franziska Wyss, Rolf Frischknecht treeze Ltd., fair life cycle thinking Kanzleistr. 4, CH-8610 Uster www.treeze.ch Phone +41 44 940 61 91, Fax +41 44 940 61 94 info@treeze.ch
Commissioner	Swiss Federal Office of Energy SFOE
Copyright	All content provided in this report is copyrighted, except when noted otherwise. Such information must not be copied or distributed, in whole or in part, without prior written consent of treeze Ltd. or the customer. A provision of this report or of files and information from this report on other websites is not permitted. Any other means of distribution, even in altered forms, require the written consent. Any citation naming treeze Ltd. or the authors of this report shall be provided to the authors before publication for verification.
Liability Statement	Information contained herein have been compiled or arrived from sources believed to be reliable. Nevertheless, the authors or their organizations do not accept liability for any loss or damage arising from the use thereof. Using the given information is strictly your own responsibility.
Version	174-Update Inverter_IEA PVPS_v1.1, 03.10.2016 15:37:00

Abbreviations and Acronyms

a	year (annum)
CH	Switzerland
GLO	global average
GWP	global warming potential
CED	cumulative energy demand
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
MJ	megajoule
PM	particulate matter
PV	photovoltaic
RER	Europe
tkm	tonne kilometre (unit for transportation services)

Summary

The technology used in inverters changed significantly in the past decade, which is why new life cycle inventories of solar inverters currently sold are established in this study. Based on information provided by three leading European producers an average inverter inventory was generated, which was then extrapolated to the following capacities: 2.5 kW, 5 kW, 10 kW, and 20 kW. Extrapolation was done using a non-linear mass versus power relationship as reported in scientific literature.

The new datasets are intended to replace the current ecoinvent inventory dataset on the 2.5 kW inverter.

The functional unit is one inverter (with a lifetime of 15 years). The inventories include the energy used for production and mounting, all components of the inverter and their upstream transportation, production processes, packaging and the disposal of packaging material and of the product itself after the use phase.

The environmental impacts of the production and disposal of inverters are analysed regarding “climate change”, “human toxicity (cancer effects)”, “human toxicity (non-cancer effects)”, “particulate matter”, “freshwater ecotoxicity” as well as “mineral, fossil and renewable resource depletion” and the main contributors to the environmental impacts of inverters are identified.

The printed board assembly causes the biggest environmental impacts, followed by the individual electronic components and the metals (copper, aluminium). Environmental impacts due to packaging, infrastructure, metal processing, transportation of raw materials and the treatment of different waste streams have negligible impacts. The energy used during production and mounting is at maximum responsible for 1.5 % of the total impact. Within the printed board assembly the integrated circuit, logic type, is the key driver of the environmental impacts of the solar inverter. The environmental impacts of the 2.5 kW inverter analysed in this study, which represents current technology, are higher than of the 2.5 kW inverter analysed ten years ago.

When discussing and comparing the results, it should be taken into account that the data availability was rather poor, requiring extrapolations and thus leading to considerable uncertainties in the generated solar inverter inventories. Nevertheless, it is recommended to use the updated life cycle inventories of solar inverters since the data quality is deemed more robust compared to the old 2.5 kW inverter.

Content

1 Introduction

Low power solar inverters transform direct electric current (DC) into alternating electric current (AC) and transform the electricity to low-voltage (230 V), which then allows the current to be fed into the grid (Jungbluth et al. 2012). Life cycle inventories of three different types of solar inverters (500 W, 2‘500 W, 500 kW) are available in the KBOB life cycle inventory database v2.2:2016 (KBOB et al. 2016). The data underlying these inventories however was derived from equipment sold and installed ten and more years ago. The technology used in inverters changed significantly since then. That is why, new life cycle inventories of inverters currently sold were established.

2 Objective and Scope

2.1 Objective

The objective of this study is to compile life cycle inventories of different power scales of solar inverters. Average life cycle inventories of low power solar inverters are compiled based on information provided by three leading European producers. Based on the data obtained, average life cycle inventories for inverters of 2.5 kW, 5 kW, 10 kW and 20 kW are generated. The life cycle inventory of the 500 W solar inverter has not been updated because no manufacturer, which delivered data, produces a 500 W inverter. The 500 kW inverter inventory is not updated because no data has been provided for high power inverters. Furthermore, their composition differs too much from low power inverters to allow extrapolation.

The environmental impacts caused by the solar inverters analysed in this study are assessed and compared with the environmental impacts of the existing 2.5 kW inverter. Moreover, the most relevant processes and materials contributing to the environmental impacts of the low power solar inverter are identified.

2.2 Functional unit and system boundaries

The functional unit of this analysis is one solar inverter of a given power output (with a lifetime of 15 years).

The product system includes the supply of materials and energy used in the production and mounting, the production processes, packaging and the disposal of packaging material and of the product itself after the use phase.

2.3 Data sources

A questionnaire was sent to several of the major inverter manufacturers in Europe in order to obtain data on currently produced inverters. Data on the production of one or several inverter models of different power output (2.5-20 kW) was obtained from three producers. The data gathered differ considerably in the level of detail. All producers provided information on the size and weight of the printed board assembly, which is the printed wiring board including all mounted components. However, only one manufacturer specified each mounted component on their printed board assembly. Hence it was assumed that all printed board assemblies are composed of the same components and only differ in total weight and size. The same has been done for individual components other than the metals copper, aluminium and steel (such as plugs, cables, polypropylene, inductor etc.), because only one manufacturer indicated all individual components that are part of the inverter but not mounted to the printed board assembly.

Since one manufacturer provided data on different inverter models, an average inverter has been compiled for this manufacturer extrapolating the data of each inverter to a common power output. The average inventories presented in this study have been compiled extrapolating the three inverters of the three manufacturers to a common power scale, which has then been extrapolated again to the power outputs of 2.5 kW, 5 kW, 10 kW and 20 kW. Extrapolation of the inverter mass (M) as a function of its power output (P) was done using the following formula for generators proposed by Caduff et al. (2011):

$M = a * P^b$,

where a = varying for the generation of the average inverter depending on the manufacturer's inverter model weight, a = 6.03 for the extrapolation of the average inverter to the different power outputs, and b = 0.68.

Extrapolation using this formula reflects a non-linear mass versus power relationship. The specific mass of inverters per power output in general decreases with an increasing nominal AC power (Jungbluth et al. 2012).

The life cycle inventories are embedded in the KBOB life cycle inventory database v2.2:2016 (KBOB et al. 2016), which is based on ecoinvent data v2.2, and the analyses were performed with SimaPro v8.0.6 (PRé Consultants 2015).

2.4 Impact assessment indicators

The environmental impacts are quantified with selected impact category indicators of the ILCD Midpoint 2011 impact assessment method, excluding long-term impacts (European Commission et al. 2012). This method was released in 2012 by the European Commission, Joint Research Centre and includes 19 midpoint impact categories. This study focuses on the following six impact categories previously identified as most relevant for the generation of PV electricity (Stolz et al. 2016):

- climate change,
- human toxicity (cancer effects),
- human toxicity (non-cancer effects),
- particulate matter,
- freshwater ecotoxicity,
- mineral, fossil and renewable resource depletion.

3 Life Cycle Inventories

3.1 Characterisation of the solar inverters

Inverters usually consist of a transformer, electronic components as control units, a case and some connectors (Jungbluth et al. 2012). Besides the production of the inverters the life cycle inventories include external packaging and the disposal of production waste and of the inverter itself at the end of life. At the end of life, the printed board assembly and the metals (aluminium, steel, copper) are recycled, whereas plastics and cardboard waste from packaging are burnt in municipal waste incineration plants.

Tab. 3.1 shows the characteristics of the inventoried average inverters of different capacities. The printed board assembly consists of the printed wiring board itself and the electrical components mounted to the printed wiring board. The total weight is calculated by adding the weight of the metals, the other individual components and the printed board assembly. The total weight does not increase linearly with an increase in power, as a consequence of the scaling factor applied for the extrapolation. In comparison to the 2.5 kW inverter available in ecoinvent data v2.2 (indicated with “old”), the new 2.5 kW inverter is lighter, its printed board assembly is smaller and lighter and less steel and copper are used.

Tab. 3.1: Characteristics of the old 2.5 kW inverter from the ecoinvent database and the average inverter with the different power outputs 2.5 kW, 5 kW, 10 kW and 20 kW.

Type	**inverter, 2.5 kW (old)**	**Average inverter, 2.5 kW**	**Average inverter, 5 kW**	**Average inverter, 10 kW**	**Average inverter, 20 kW**
Unit	[kg]	[kg]	[kg]	[kg]	[kg]
Total weight	18.7	11.2	18.0	28.9	46.2
Copper	5.5	1.9	3.1	4.9	7.9
Aluminium	1.4	5.0	8.0	12.8	20.5
Steel	9.8	0.9	1.5	2.3	3.7
Other individual components	0.3	2.2	3.6	5.7	9.2
Printed board assembly	1.7	1.2	2.0	3.1	5.0
Printed wiring board	0.7	0.3	0.5	0.8	1.4

3.2 Manufacturing and disposal of solar inverters

All life cycle inventories of the manufacturing and disposal of solar inverters are structured identically. The inventories list first the energy needed for the production and mounting of one inverter and the materials for the casing and other individual components. Individual components include metals, plastics, cables, plugs, inductors and integrated circuits. Integrated circuits and a smaller amount of inductors, cables and plugs are also present on the printed board. All inputs listed under printed board assembly are, in contrast to individual components, fixed to the printed board. The printed board assembly includes capacitors, resistors, transformers, connectors, inductors, transistors, diodes, plugs, cables, some glass fibre reinforced plastic, tin and ferrite.

Furthermore, metal processing and an infrastructure demand for the machines and the production plant are included. As already mentioned, different packaging materials are considered as well as the transport of raw materials to the production site. Finally, the inventories include data on water usage and the treatment of different waste streams.

The printed board assembly of the manufacturer specifying all components of a printed board assembly is built with the lead-free surface mount technique (which is more common nowadays). Therefore the printed boards of the average inventories are also produced with the surface mount technique. In contrast, the inventory of the old “inverter, 2500W, at plant” assumes the through-hole mounting technique for the printed board assembly production.

The transportation demand in tkm of the raw materials has been calculated using standard transport distances. The average life cycle inventories for inverters with the capacities of 2.5 kW, 5 kW, 10 kW and 20 kW are shown in Tab. 3.2.

Tab. 3.2: Life cycle inventories of manufacture and disposal of solar inverters of 2.5 kW, 5 kW, 10 kW and 20 kW

	Name	Location	InfrastructureProcess	Unit	inverter, 2.5 kW, average, at plant	inverter, 5 kW, average, at plant	inverter, 10 kW, average, at plant	inverter, 20 kW, average, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1			
	Unit				unit	unit	unit	unit			
product	inverter, 2.5 kW, average, at plant	RER	1	unit	1	0	0	0			
product	inverter, 5 kW, average, at plant	RER	1	unit	0	1	0	0			
product	inverter, 10 kW, average, at plant	RER	1	unit	0	0	1	0			
product	inverter, 20 kW, average, at plant	RER	1	unit	0	0	0	1			
energy use	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	1.06E+1	1.69E+1	2.71E+1	4.34E+1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from two European inverter manufacturers;
	light fuel oil, burned in industrial furnace 1MW, non-modulating	CH	0	MJ	2.26E-1	3.61E-1	5.79E-1	9.28E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from two European inverter manufacturers;
	natural gas, burned in power plant	DE	0	MJ	3.57E+0	5.72E+0	9.17E+0	1.47E+1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from two European inverter manufacturers;
	district heat, from municipal waste incineration plant	CH	0	MJ	9.21E+0	1.47E+1	2.36E+1	3.79E+1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from two European inverter manufacturers;
individual components	aluminium, production mix, cast alloy, at plant	RER	0	kg	4.77E+0	7.64E+0	1.22E+1	1.96E+1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	aluminium alloy, AlMg3, at plant	RER	0	kg	2.12E-1	3.39E-1	5.43E-1	8.70E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	copper, at regional storage	RER	0	kg	1.91E+0	3.06E+0	4.90E+0	7.86E+0	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	steel, low-alloyed, at plant	RER	0	kg	9.07E-1	1.45E+0	2.33E+0	3.73E+0	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use; data on the production of three inverters by two European producers
	polypropylene, granulate, at plant	RER	0	kg	8.82E-1	1.41E+0	2.27E+0	3.63E+0	1	1.60	(3,4,1,3,4,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	polycarbonate, at plant	RER	0	kg	2.02E-1	3.24E-1	5.19E-1	8.32E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	cable, connector for computer, without plugs, at plant	GLO	0	m	1.31E-1	2.10E-1	3.37E-1	5.40E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	inductor, ring core choke type, at plant	GLO	0	kg	8.71E-1	1.40E+0	2.24E+0	3.58E+0	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	integrated circuit, IC, logic type, at plant	GLO	0	kg	6.61E-2	1.06E-1	1.70E-1	2.72E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	ferrite, at plant	GLO	0	kg	3.49E-2	5.59E-2	8.96E-2	1.44E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	plugs, inlet and outlet, for network cable, at plant	GLO	0	unit	3.48E+0	5.58E+0	8.93E+0	1.43E+1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	1.31E-1	2.09E-1	3.35E-1	5.37E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
printed board assembly	printed wiring board, surface mount, lead-free surface, at plant	GLO	0	m2	1.01E-1	1.62E-1	2.60E-1	4.16E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	tin, at regional storage	RER	0	kg	9.59E-3	1.54E-2	2.46E-2	3.94E-2	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	connector, clamp connection, at plant	GLO	0	kg	2.44E-2	3.91E-2	6.26E-2	1.00E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	inductor, ring core choke type, at plant	GLO	0	kg	1.31E-1	2.09E-1	3.35E-1	5.37E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	inductor, miniature RF chip type, MRFI, at plant	GLO	0	kg	1.10E-3	1.77E-3	2.83E-3	4.53E-3	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	integrated circuit, IC, logic type, at plant	GLO	0	kg	1.55E-1	2.49E-1	3.99E-1	6.39E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	integrated circuit, IC, memory type, at plant	GLO	0	kg	1.87E-3	3.00E-3	4.81E-3	7.70E-3	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	transistor, unspecified, at plant	GLO	0	kg	1.92E-2	3.07E-2	4.92E-2	7.89E-2	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	transistor, SMD type, surface mounting, at plant	GLO	0	kg	4.17E-2	6.69E-2	1.07E-1	1.72E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	diode, glass-, SMD type, surface mounting, at plant	GLO	0	kg	2.01E-3	3.22E-3	5.15E-3	8.25E-3	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	light emitting diode, LED, at plant	GLO	0	kg	1.44E-5	2.31E-5	3.69E-5	5.92E-5	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	capacitor, film, through-hole mounting, at plant	GLO	0	kg	1.66E-1	2.67E-1	4.27E-1	6.84E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	capacitor, electrolyte type, > 2cm height, at plant	GLO	0	kg	2.57E-1	4.12E-1	6.60E-1	1.06E+0	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;

Tab. 3.2: Life cycle inventories of manufacture and disposal of solar inverters of 2.5 kW, 5 kW, 10 kW and 20 kW (continued)

	Name	Location	InfrastructureProcess	Unit	inverter, 2.5 kW, average, at plant	inverter, 5 kW, average, at plant	inverter, 10 kW, average, at plant	inverter, 20 kW, average, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1			
	Unit				unit	unit	unit	unit			
	capacitor, electrolyte type, < 2cm height, at plant	GLO	0	kg	6.71E-3	1.08E-2	1.72E-2	2.76E-2	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	capacitor, SMD type, surface-mounting, at plant	GLO	0	kg	1.33E-3	2.14E-3	3.42E-3	5.49E-3	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	resistor, wirewound, through-hole mounting, at plant	GLO	0	kg	1.12E-3	1.79E-3	2.87E-3	4.60E-3	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	resistor, SMD type, surface mounting, at plant	GLO	0	kg	4.57E-3	7.33E-3	1.17E-2	1.88E-2	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	ferrite, at plant	GLO	0	kg	2.55E-5	4.09E-5	6.55E-5	1.05E-4	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	transformer, low voltage use, at plant	GLO	0	kg	4.01E-2	6.43E-2	1.03E-1	1.65E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	plugs, inlet and outlet, for network cable, at plant	GLO	0	unit	2.79E-1	4.47E-1	7.16E-1	1.15E+0	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	2.56E-2	4.10E-2	6.57E-2	1.05E-1	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	cable, ribbon cable, 20-pin, with plugs, at plant	GLO	0	kg	2.40E-4	3.84E-4	6.16E-4	9.86E-4	1	1.31	(2,3,1,3,3,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
processing	sheet rolling, steel	RER	0	kg	9.07E-1	1.45E+0	2.33E+0	3.73E+0	1	1.21	(1,1,1,1,1,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use; Applied as well on the production data of an inverter of an European producer
	wire drawing, copper	RER	0	kg	1.91E+0	3.06E+0	4.90E+0	7.86E+0	1	1.21	(1,1,1,1,1,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use; Applied as well on the production data of an inverter of an European producer
	section bar extrusion, aluminium	RER	0	kg	4.77E+0	7.64E+0	1.22E+1	1.96E+1	1	1.21	(1,1,1,1,1,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use; Applied as well on the production data of an inverter of an European producer
	steel product manufacturing, average metal working	RER	0	kg	1.92E-2	3.08E-2	4.93E-2	7.90E-2	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
infrastructure	metal working factory	RER	1	unit	1.10E-8	1.76E-8	2.82E-8	4.51E-8	1	3.05	(1,1,1,1,1,5,BU:3); Calculation, based on annual production of electronic component production plant; taken from the ecoinvent v2.2 inverter dataset;
packaging	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	6.60E-1	1.06E+0	1.69E+0	2.71E+0	1	1.21	(1,1,1,1,1,5,BU:1.05); data on the production of an inverter by a European producer;
	folding boxboard, FBB, at plant	RER	0	kg	1.16E+0	1.85E+0	2.97E+0	4.75E+0	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
	packaging film, LDPE, at plant	RER	0	kg	1.15E-2	1.84E-2	2.95E-2	4.73E-2	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
transport	transport, lorry >16t, fleet average	RER	0	tkm	6.76E-1	1.08E+0	1.74E+0	2.78E+0	1	2.09	(4,5,na,na,na,na,BU:2); Standard distance 60km incl. disposal;
	transport, freight, rail	RER	0	tkm	2.25E+0	3.61E+0	5.79E+0	9.27E+0	1	2.09	(4,5,na,na,na,na,BU:2); Standard distances 200km;
	transport, transoceanic freight ship	OCE	0	tkm	2.03E+1	3.25E+1	5.21E+1	8.34E+1	1	2.09	(4,5,na,na,na,na,BU:2); Estimation: 18000km;
emission air, unspecified	Heat, waste	-	-	MJ	3.80E+1	6.09E+1	9.75E+1	1.56E+2	1	1.22	(2,3,1,1,1,5,BU:1.05); Calculation;
technosphere	tap water, at user	RER	0	kg	1.99E+1	3.18E+1	5.10E+1	8.17E+1	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
resource, in water	Water, unspecified natural origin, DE	-	-	m3	3.78E-2	6.06E-2	9.71E-2	1.56E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
disposal	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	0	m3	1.99E-2	3.18E-2	5.10E-2	8.17E-2	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
	disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	0	kg	1.82E+0	2.91E+0	4.66E+0	7.47E+0	1	1.25	(2,3,1,5,1,5,BU:1.05); disposal of the packaging materials;
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	0	kg	1.15E-2	1.84E-2	2.95E-2	4.73E-2	1	1.25	(2,3,1,5,1,5,BU:1.05); disposal of the packaging materials;
	disposal, treatment of printed wiring boards	GLO	0	kg	1.22E+0	1.96E+0	3.14E+0	5.02E+0	1	1.25	(2,3,1,5,1,5,BU:1.05); Data from three European inverter manufacturers ; recycled after use;
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	2.43E-1	3.89E-1	6.23E-1	9.98E-1	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;
	disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	0	kg	1.28E-2	2.06E-2	3.30E-2	5.28E-2	1	1.34	(3,4,1,3,3,5,BU:1.05); data on the production of an inverter by a European producer;

4 Life Cycle Impact Assessment

4.1 Overview

This chapter contains the environmental impact assessment results and highlights the main drivers of the environmental impacts of inverters. The impacts are grouped into seven categories, namely the “printed board assembly (printed board including all mounted components)”, the metals “copper”, “aluminium” and “steel”, “other individual components (including all components besides the metals not being attached to the printed board)”, “energy” and “others”. Environmental impacts due to packaging, infrastructure, metal processing, transportation of raw materials and the treatment of different waste streams are aggregated to the category “others” since their individual contributions are small. The energy used during production is at maximum responsible for 1.5 % of the total impact and shown separately.

Since this study compiled inventories of low power solar inverters, the results are compared to the environmental impacts of the old 2.5 kW inverter. The main drivers for each impact category of the new average inverter are for all inverter capacities the same, due to the extrapolation made from one average inverter.

4.2 Comparison of solar inverters regarding the six impact categories

4.2.1 Climate change

For both the ecoinvent inverter and the average inverter, the printed board assembly has the biggest impact on climate change (see Fig. 4.1). The printed board assembly causes 59 % of the total impact for the new and 66 % of the total impact for the old inverter. The integrated circuit, logic type, of the printed board assembly is responsible for 42 % and aluminium for 6 % of the new inverter’s total climate change impact. The impact of the category “other individual components” of the old inverter is almost zero, because only the metals copper, steel and aluminium as well as two different plastics belong to the category “individual components”. Within the individual components the integrated circuit, logic type, amounts to 18 % and the ring core choke to another 10 % of the new inverter’s impact. The climate change impact of the energy used during the production and mounting of the old 2.5 kW inverter is four times higher than for the new inverter, but in total negligible.

For the ecoinvent inverter with a capacity of 2.5 kW the integrated circuit, logic type, of the printed board assembly only carries 16 % of the total climate change impact. The printed board makes up 13 % and steel 10 %.

In total the impact on climate change of the new 2.5 kW inverter is more than twice the impact of the old 2.5 kW on climate change and amounts to 358 kg CO_2-eq.

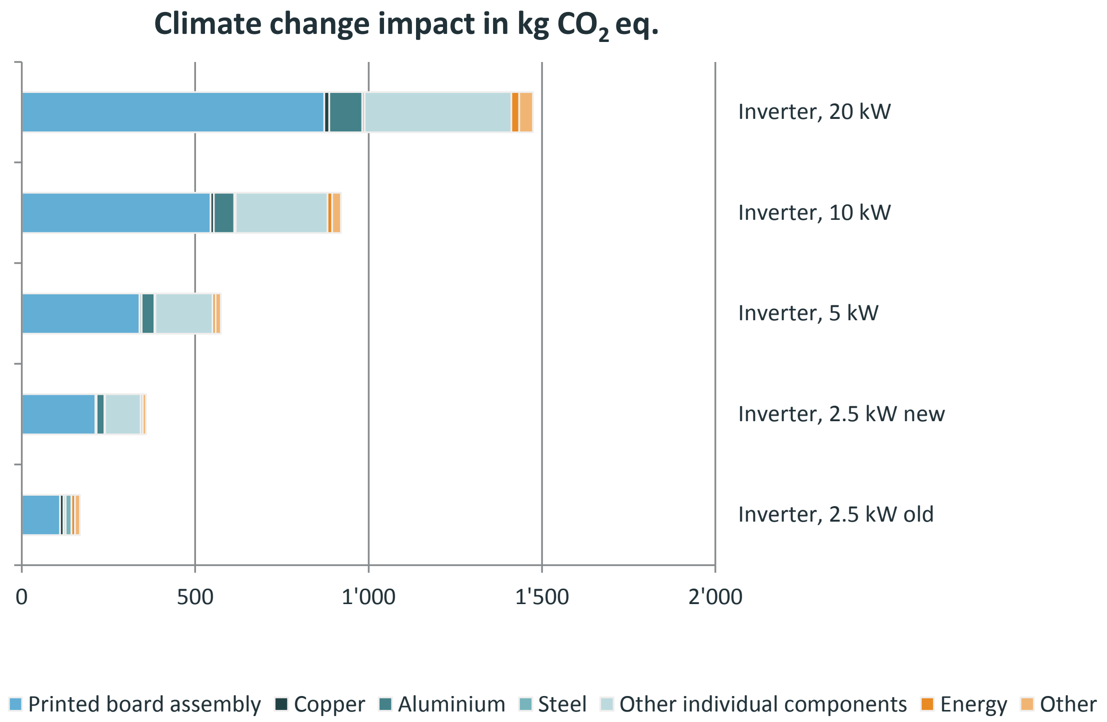

Fig. 4.1: Greenhouse gas emissions of manufacture and disposal of low power solar inverters, quantified in kg CO_2-eq (IPCC 2013,Chapter 8).

4.2.2 Human toxicity, cancer effects

Fig. 4.2 reveals that the old and new inverter with the capacity 2.5 kW cause about the same impact on human toxicity, cancer effects. The printed board assembly of the new inverter causes 50 % of the cancer effects and that of the old inverter 27 %. The integrated circuit, logic type, within the printed board assembly as well as the ring core choke make up 37 % and 7 %, respectively, of the total impact on cancer effects in case of the new inverter. In the new inverter aluminium is responsible for 16 %, steel for 5 % and copper for 4 % of the total impact. Whereas, in case of the old inverter, steel causes 49 %, copper 11 % and aluminium 4 % of the total impact on human toxicity, cancer effects.

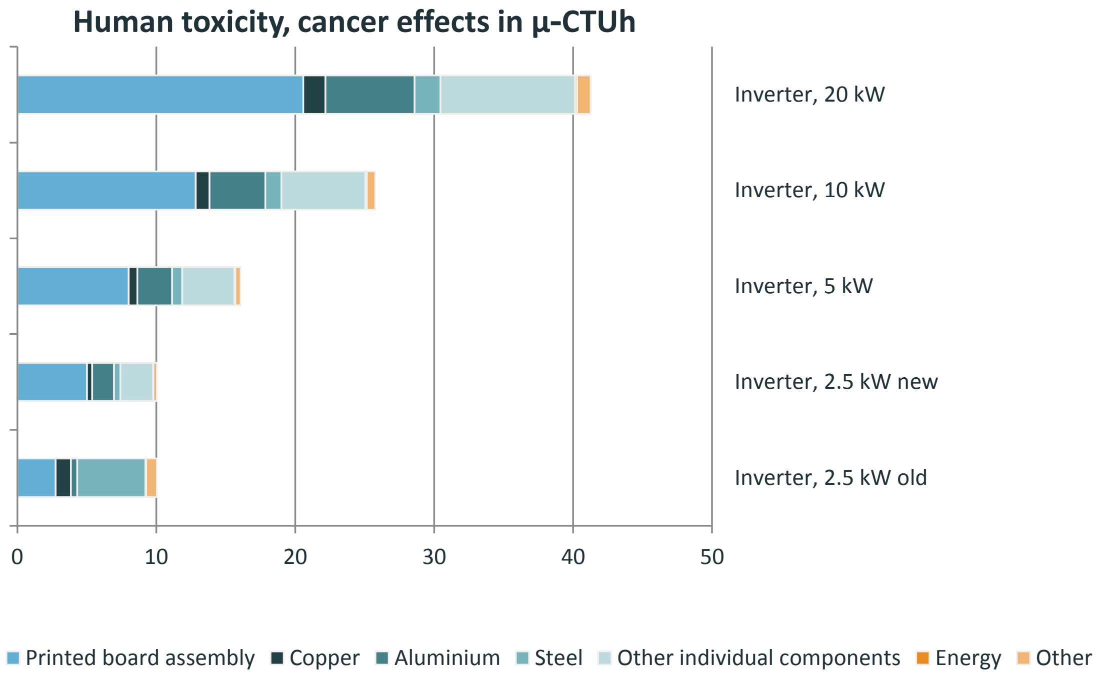

Fig. 4.2: Impacts of manufacture and disposal of low power solar inverters on human toxicity, cancer effects, quantified in µ-CTUh.

4.2.3 Human toxicity, non-cancer effects

In case of the new inverter the printed board assembly has the biggest impact on human toxicity, non-cancer effects, with 55 % (see Fig. 4.3), while copper dominates the non-cancer effects of the old inverter by 59 %. Besides copper, the integrated circuit, logic type, contributes with 11 %, steel with 8 % and the capacitor, film with 6 % to the total non-cancer effects of the old inverter.

The dominating impacts of the new inverter stem from the integrated circuit, logic type, of the printed board assembly (45 %), the integrated circuit, logic type, of the individual components category (19 %), copper (16 %) and aluminium (5 %).

The impact on human toxicity, non-cancer effects, of the new 2.5 kW solar inverter is 30 % higher than the impact of the old 2.5 kW inverter.

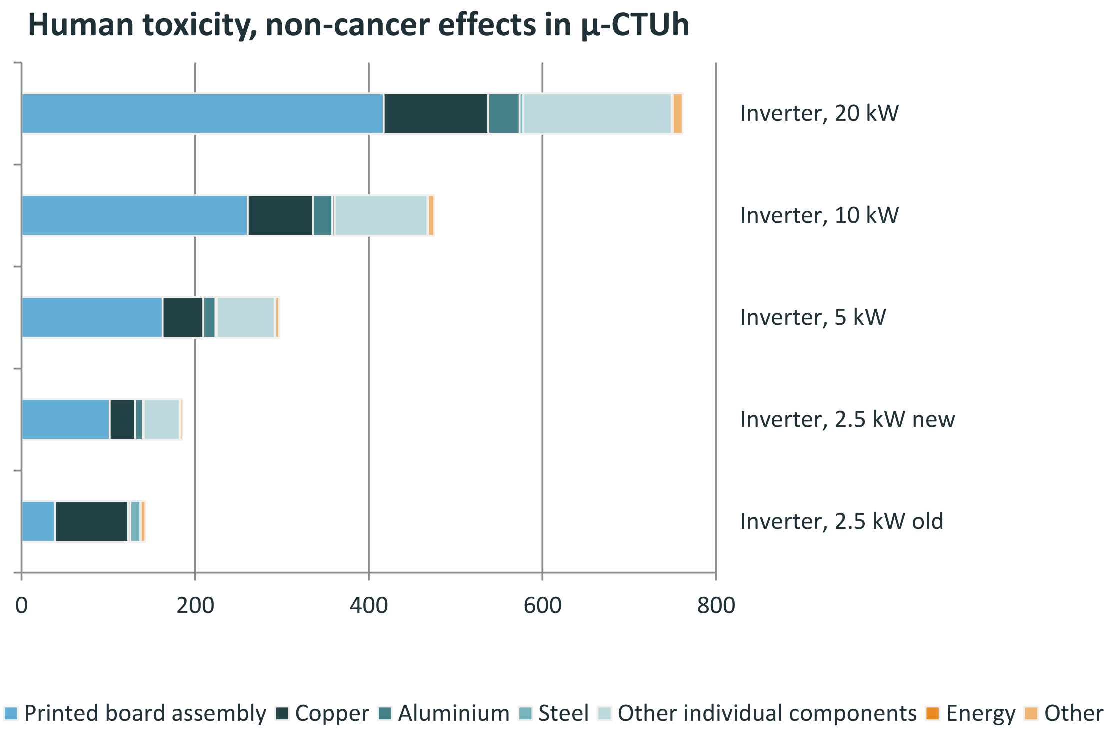

Fig. 4.3: Impacts of manufacture and disposal of low power solar inverters on human toxicity, non-cancer effects, quantified in µ-CTUh.

4.2.4 Particulate matter (PM)

The printed board assembly makes up 52 % and the other individual components 26 % of the total PM emissions of the new inverter (see Fig. 4.4). Within the printed board assembly the integrated circuit, logic type, emits most with 65 % and within the individual components category 58 %. Copper used in the new inverter emits an additional 11 % of particulate matter.

Copper emits 43 %, the integrated circuit, logic type, and steel each 8 % and the capacitor, film 7 % of all particular matter emissions of the old inverter.

The new 2.5 kW solar inverter causes 34 % higher particulate matter emissions than the old 2.5 kW inverter.

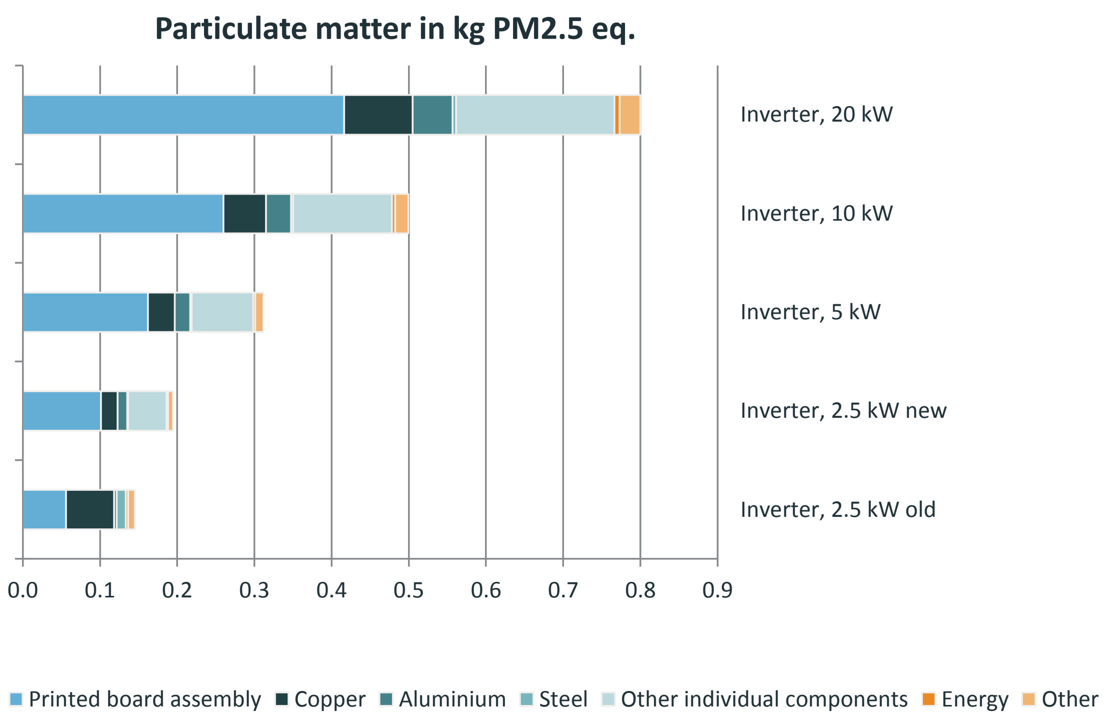

Fig. 4.4: Impacts of manufacture and disposal of low power solar inverters on particulate matter, quantified in kg PM2.5 eq.

4.2.5 Freshwater ecotoxicity

The printed board assembly dominates the impact on freshwater ecotoxicity of both the new and the old inverter with a share of 67 % and 55 %, respectively (see Fig. 4.5). The impact on freshwater ecotoxicity of the new 2.5 kW inverter is almost three times as high as the impact of the old 2.5 kW inverter. The total impact of the old inverter is dominated by the integrated circuit, logic type (33 %), copper (29 %), the capacitor, film (10 %), steel (10 %) and the printed board (8 %).

The integrated circuit, logic type of the printed board assembly of the new inverter causes 61 % and the one of the individual components further 26 % of the total impact on freshwater ecotoxicity.

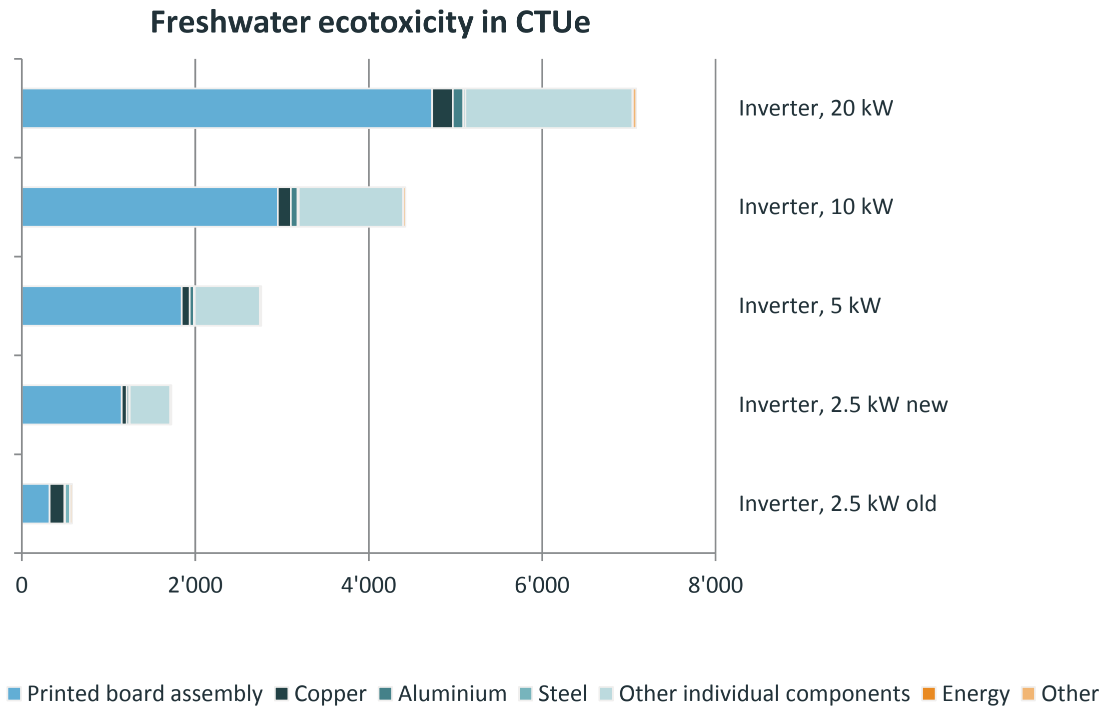

Fig. 4.5: Impacts of manufacture and disposal of low power solar inverters on freshwater ecotoxicity, quantified in CTUe.

4.2.6 Mineral, fossil and renewable resource depletion

The impact on mineral, fossil and renewable resource depletion of the old 2.5 kW inverter is twice as high as the impact of the new 2.5 kW inverter (see Fig. 4.6). 96 % of the impacts are caused by the printed board assembly used in the old inverter. Within the printed board assembly, most impact is caused by the capacitor, Tantalum (65 %) and the capacitor, film (25 %).

The printed board assembly dominates the overall impact of the new inverter as well with 75 %. The main drivers of resource depletion are the integrated circuit, logic type of the printed board assembly (42 %), the capacitor, film (27 %) and the integrated circuit, logic type, of the individual components (18 %).

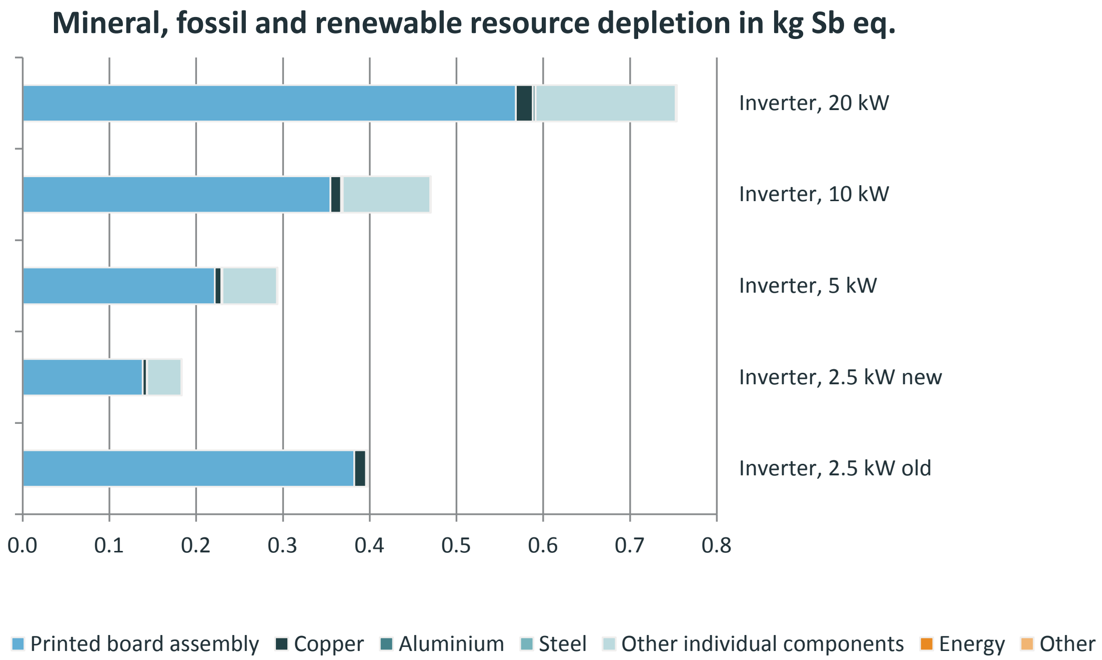

Fig. 4.6: Impacts of manufacture and disposal of low power solar inverters on mineral, fossil and renewable resource depletion, quantified in kg Sb eq.

5 Data quality and uncertainty

Since not many inverter manufacturers provided data on the production of inverters, the data quality is rather poor and limited to low power inverters. Furthermore, data of the different manufacturers differ substantially regarding the weight and the materialisation of the inverter. There is a trend to produce lighter inverters with less copper[1]. Hence, all data gathered have been averaged to build a more robust inventory. For the different power capacities, the inventory was then extrapolated according to Caduff et al. (2011). The individual components as well as the mounted components of the printed board assembly of the average inverter, were not averaged but directly taken from one single inverter model of one of the three manufacturers providing data. This is a clear limitation since the printed board assembly, followed by the individual components and the metals of the new inverters are the main drivers regarding all analysed impact categories. Hence, the components have a big influence on the total environmental impacts of an inverter. That is why the new 2.5 kW inverter causes higher environmental impacts in most impact categories than the old 2.5 kW inverter, although being lighter in total and having a smaller printed board.

Despite these uncertainties, it is recommended to use the updated life cycle inventories of solar inverters since the data quality is deemed more robust compared to the old 2.5 kW inverter.

[1] Personal communication, European manufacturer of solar inverters, 16.08.2016

Acknowledgement

We gratefully acknowledge the kind support of Susanne Schidler, Technikum Wien, in the data collection for the life cycle assessment of solar inverters.

References

Caduff et al. 2011	Caduff M., Huijbregts M. A. J., Althaus H.-J. and Hendriks A. J. (2011) Power-Law Relationships for Estimating Mass, Fuel Consumption and Costs of Energy Conversion Equipments. In: Environmental Science & Technology, 45(2), pp. 751-754.
European Commission et al. 2012	European Commission, Joint Research Centre and Institute for Environment and Sustainability (2012) Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information. First Edition. Publication Office of the European Union, Luxembourg.
IPCC 2013	IPCC (2013) The IPCC fifth Assessment Report - Climate Change 2013: the Physical Science Basis. Working Group I, IPCC Secretariat, Geneva, Switzerland.
Jungbluth et al. 2012	Jungbluth N., Stucki M., Flury K., Frischknecht R. and Buesser S. (2012) Life Cycle Inventories of Photovoltaics. ESU-services Ltd., Uster, CH, retrieved from: www.esu-services.ch.
KBOB et al. 2016	KBOB, eco-bau and IPB (2016) KBOB-Empfehlung 2009/1:2016: Ökobilanzdaten im Baubereich, Stand Juli 2016. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: http://www.bbl.admin.ch/kbob/00493/00495/index.html?lang=de.
PRé Consultants 2015	PRé Consultants (2015) SimaPro 8.0.6, Amersfoort, NL.
Stolz et al. 2016	Stolz P., Frischknecht R., Wyss F. and de Wild Scholten M. (2016) PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots, version 2.0. treeze Ltd. commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.