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Life Cycle Assessment of Photo-voltaic Module Recycling

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Abbreviations and Acronyms

a	year (annum)
CdTe	cadmium telluride
CH	Switzerland
c-Si	crystalline silicon
EUR	euro
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
PEF	product environmental footprint
PV	photovoltaic
RER	Europe
tkm	tonne kilometre (unit for transportation services)
USD	US dollars
WEEE	waste electrical and electronic equipment

Summary

With the rapid and accelerating growth of PV module installation and an increase of PV modules from the eighties and nineties reaching their end of life, their proper end of life treatment gets into focus. This report deals with the efforts, the environmental impacts and the recovered materials of PV module recycling. In this report, the environmental life cycle assessment of the current generation recycling of c-Si and CdTe PV modules is described. Due to the still limited waste stream today, crystalline-silicon (c-Si) PV modules are mainly treated in recycling plants designed for treatment of laminated glass, metals or electronic waste. Only the bulk materials glass, aluminium and copper are recovered, while the cells and other materials such as plastics are incinerated. Cadmium-telluride (CdTe) PV modules have been treated in dedicated recycling plants for many years and life cycle inventories of this process have been published. The semiconductor is recovered in addition to glass and copper.

Life cycle inventories of the recycling of c-Si and CdTe PV modules are compiled following two modelling approaches related to recycling. The cut-off approach allocates the total efforts of the recycling process economically to the treatment of the used PV module and the recovered products. The end-of-life approach considers the recycling process separately from the potentially avoided burdens due to recovered materials. The life cycle impact assessment is done based on six environmental indicators previously identified as most relevant for PV electricity: particulate matter, freshwater ecotoxicity, human toxicity non-cancer effects, human toxicity cancer effects, mineral, fossil and renewable resource depletion and climate change.

The life cycle inventories according to the cut-off approach can be applied to complement existing life cycle inventory data on PV systems. The environmental impacts of the recycling of c-Si PV modules are very small (maximum 0.8 %) compared to the impacts caused by the production of a 3 kWp PV system mounted on a slanted roof. In the case of CdTe PV module recycling, the treatment of the PV panels has the highest but still rather minor contribution in the indicator climate change (4.3 %).

The life cycle inventories according to the end-of-life approach allow an assessment of the net environmental benefits of recycling. The recovery of glass, metals, and semiconductor material from c-Si and CdTe PV modules causes lower environmental impacts than the extraction, refinement and supply of the respective materials from primary resources. The highest potential benefits are observed in the indicator mineral, fossil and renewable resource depletion.

The data quality of the recycling of c-Si PV modules is classified as satisfactory since only limited information is available. In contrast, the data quality of CdTe PV module recycling is considered very good.

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Content

1 Introduction

Life cycle inventories (LCI) of the production of photovoltaic (PV) modules have been established many years ago and updated regularly since then (see e.g. Frischknecht et al. 2015). In contrast, the data basis for the assessment of the end-of-life treatment of PV modules, apart from the cadmium telluride (CdTe) technology, has been weak so far. The fact that PV deployment at a significant level started only in the 1990s and the long life time of PV modules result in a relatively small waste stream today. However, the amount of used crystalline silicon (c-Si) PV panels to be recycled is expected to rise strongly after the year 2020 (Weckend et al. 2016; Wambach & Sander 2015). CdTe PV modules have been treated in dedicated recycling plants for many years and life cycle inventories of this process have been published by Sinha et al. (2012).

The objective and scope of this study are described in chapter 2. The life cycle inventories of c-Si and CdTe PV module recycling are presented in chapter 3. Chapter 4 contains the results of the life cycle impact assessment. The data quality and the sources of uncertainty are documented in chapter 5.

2 Objective and scope

2.1 Objective

The objective of this study is to compile life cycle inventories of the recycling of c-Si and CdTe PV modules. Different life cycle inventories are established following the cut-off approach and the end-of-life approach (see subchapter 2.3). The environmental impacts of the PV module recycling process are analysed based on six indicators and the main contributors to the recycling efforts are identified. For the end-of-life approach, the potential environmental benefits from recovered materials are compared to the environmental impacts caused by the recycling process.

2.2 Functional unit

The functional unit of this analysis is the recycling of 1 kg of used framed c-Si and unframed CdTe PV modules at the place of installation. The mounting structure and the electric installation required for PV systems are not included in the life cycle inventories of the recycling process and of the potential benefits due to recycling since they are treated separately from the PV modules.

2.3 Modelling approaches

Different modelling approaches exist for recycling processes (Frischknecht 2010). The life cycle inventories of c-Si and CdTe PV module recycling were compiled according to two different approaches:

- *Cut-off approach*
  The recycling efforts are economically allocated among the treatment process and all the recovered materials with a positive economic value. Economic allocation takes the mass fraction and the (relative) price of the co-products into account. The cut-off recycling approach is required by the ecoinvent quality guidelines (Frischknecht et al. 2007) and is therefore suited to complement the existing life cycle inventories of PV systems.
- *End-of-life approach*
  The takeback and recycling of the PV modules is considered separately from the potential benefits gained by recovered materials. The potential benefits are calculated by awarding credits for the avoided environmental impacts caused by the primary production of replaced products and charging the impacts of secondary material production. This modelling approach can be used to illustrate the net environmental impacts of PV module recycling. A similar approach is required in the Product Environmental Footprint (PEF) Pilots by the European Commission (2013; 2015). However, the approach applied in this study follows a 100/0 allocation where the potential benefits are fully allocated to the recyclable material, which is suited to quantify the overall net environmental impacts of the recycling process. In contrast, the end-of-life approach required in

the PEF Pilots uses a 50/50 allocation, which means that both the product to be recycled and the products using secondary material receive half of the credits.

2.4 Data sources

A questionnaire was sent to several recycling companies in central Europe treating c-Si PV panels by Karsten Wambach (Wambach-Consulting) between 2015 and 2016. The recycling companies were asked about information on their energy and material consumption and the amount of recovered material. The information provided by the two responding recyclers was used to establish an average life cycle inventory of first generation recycling of c-Si PV panels. Since c-Si PV modules are currently not recycled in dedicated facilities (Wambach & Sander 2015), the present life cycle inventory represents the recycling process in plants designed for laminated glass (e.g. from cars) and metals, respectively.

The life cycle inventories of the first generation recycling of CdTe PV modules were compiled based on publicly available information (Sinha et al. 2012).

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

2.5 Impact assessment indicators

The environmental impacts of the c-Si and CdTe PV module recycling were quantified with selected impact category indicators of the ILCD Midpoint 2011 impact assessment method (European Commission et al. 2012). This study focuses on the following six impact categories previously identified as most relevant for the generation of PV electricity (Stolz et al. 2016):

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

Long-term emissions were not included in the impact assessment.

3 Life cycle inventories

3.1 Overview

The life cycle inventories of c-Si and CdTe PV modules are described in subchapters 3.2 and 3.3, respectively. For both technologies, a short description of the process is presented first, followed by the life cycle inventories according to the cut-off approach and the end-of-life approach.

3.2 c-Si PV modules

3.2.1 Description of the process

The average weight of c-Si PV modules (13.2 kg/m^2) was calculated based on the bill of material and the installed capacity of monocrystalline and multicrystalline Si PV modules as reported by Stolz et al. (2016). Based on a previous study (Latanussa et al. 2016), it was estimated that the used c-Si PV modules are transported by lorry over a distance of 500 km from the place of installation to a collection point (100 km) and subsequently to the recycling facility (400 km). On-site transportation of c-Si PV modules is accomplished with a four-wheel loader (0.045 MJ/kg).

In first generation recycling processes, c-Si PV modules are treated in reycling plants designed for laminated glass, metals or electric and electronic waste. The data available in this study were collected in recycling companies designed for laminated glass and metals, respectively. The c-Si PV modules are mechanically treated, yielding the bulk materials glass cullets, aluminium scrap and copper scrap. The average electricity demand of the machines is 0.277 kWh/kg, with a large difference between the two recycling plants. The mechanical recycling of c-Si PV modules does not require any auxiliary materials.

The plastic material fraction (0.125 kg/kg) is disposed of in municipal incineration plants and to a lower degree in sanitary landfills. It is mainly composed of polymers and foils but usually also includes the c-Si cell and silver.

3.2.2 Cut-off approach

When applying the cut-off approach, the total efforts of c-Si PV module recycling are allocated economically to the co-products waste treatment, glass cullets, aluminium scrap and copper scrap by using the allocation factors listed in Tab. 3.1. The shares of the individual fractions of recovered materials from PV module recycling were determined based on the information obtained from the recycling companies. The price of c-Si PV module treatment is approximately 0.170-0.250 EUR/kg and the costs of transportation amount to 0.025-0.105 EUR/kg (Brellinger 2014), which yields average total waste treatment costs of 0.275 EUR/kg. In general, the prices of all recovered materials exhibit high volatility. The price of glass cullets was estimated by Karsten

Wambach[1] and the prices of aluminium and copper scrap were taken from EUWID (2016).

Tab. 3.1 Mass fractions and prices used to calculate economic allocation factors for the cut-off modelling approach of c-Si PV module recycling (personal communication Karsten Wambach, Wambach-Consulting, 15.06.2016; Brellinger 2014; EUWID 2016).

c-Si recycling	Mass fraction (-)	Price	Allocation factor
	-	EUR/kg	-
Treatment	1.000	0.275	**0.472**
Glass cullets	0.717	0.020	**0.025**
Aluminium scrap	0.104	0.700	**0.125**
Copper scrap	0.055	4.000	**0.379**

The life cycle inventories of c-Si PV module recycling according to the cut-off modelling approach are presented in Tab. 3.2. The major part of the recycling efforts is allocated to the waste treatment and the copper scrap.

Tab. 3.2 Life cycle inventory of the treatment of used c-Si PV modules in a first generation recycling process and of the recovered materials according to the cut-off approach.

	Name	Location	InfrastructureProcess	Unit	treatment, c-Si PV module	glass cullets, recovered from c-Si PV module treatment	aluminium scrap, recovered from c-Si PV module treatment	copper scrap, recovered from c-Si PV module treatment	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	treatment, c-Si PV module	RER	0	kg	1	0	0	0			
	glass cullets, recovered from c-Si PV module treatment	RER	0	kg	0	1	0	0			
	aluminium scrap, recovered from c-Si PV module treatment	RER	0	kg	0	0	1	0			
	copper scrap, recovered from c-Si PV module treatment	RER	0	kg	0	0	0	1			
technosphere	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	1.31E-1	9.51E-3	3.33E-1	1.90E+0	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers; Economic allocation;
	diesel, burned in building machine	GLO	0	MJ	2.12E-2	1.54E-3	5.40E-2	3.09E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	5.52E-2	4.02E-3	1.41E-1	8.03E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	3.59E-3	2.61E-4	9.14E-3	5.22E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers; Economic allocation;
	transport, lorry >16t, fleet average	RER	0	tkm	2.36E-1	1.72E-2	6.01E-1	3.43E+0	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance: 500 km; Economic allocation; Latanussa et al. 2016

3.2.3 End-of-life approach

The takeback and recycling of c-Si PV modules and the potentially avoided burdens due to recovered materials are considered separately in the end-of-life approach. The life cycle inventory of first generation c-Si PV module takeback and recycling is shown in Tab. 3.3.

[1] Personal communication Karsten Wambach, Wambach-Consulting, 15.06.2016.

Tab. 3.3 Life cycle inventory of the takeback and recycling of used c-Si PV modules in a first generation recycling process according to the end-of-life approach.

	Name	Location	InfrastructureProcess	Unit	takeback and recycling, c-Si PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	takeback and recycling, c-Si PV module	RER	0	kg	1			
technosphere	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	2.77E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers;
	diesel, burned in building machine	GLO	0	MJ	4.49E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers;
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	1.15E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers;
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	1.00E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Average based on information from two German recyclers;
	transport, lorry >16t, fleet average	RER	0	tkm	5.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance: 500 km;

The potential environmental benefits gained by recovered materials are calculated based on the methodology applied in Stolz et al. (2016). A 100/0 allocation was used in order to be able to assess the overall net environmental impacts of c-Si PV module recycling. The largest fraction of recovered material is glass cullet (0.717 kg/kg), which is mainly used in recycled foam glass production. Since detailed life cycle inventory data on this process are missing, the avoided burdens were calculated based on the production of flat glass. Using recycled glass cullets in glass production avoids the consumption of primary materials such as limestone, silica sand and soda powder. The geogenic CO_2-emissions caused by these raw materials in flat glass production are prevented (Held & Ilg 2011), which amount to 0.208 kg CO_2 eq/kg flat glass (Kellenberger et al. 2007). Because the melting of the glass cullets takes less energy than the melting of limestone and silica sand, heavy fuel oil and natural gas can additionally be saved. Held and Ilg (2011) assumed an energy reduction potential in the melting process of around 30 % when replacing 100 % input material by glass cullets. The recycling efficiency was estimated at 90 % (Sinha et al. 2012).

The aluminium scrap (0.104 kg/kg) is recovered from the frame of the c-Si PV module. In addition, copper scrap (0.055 kg/kg) is recovered, which was initally used in the junction box and the wires. Efforts to produce secondary metals from scrap were taken into account for aluminium and copper. These secondary metals are potentially avoiding primary aluminium and primary copper production, respectively. Benefits for recycling are granted only for the net surplus amount of recycled material, which leaves the PV system (see also EN 15804 2013). According to ecoinvent data v2.2:2016 the recycled content of the $AlMg_3$ alloy used in the frame is 56 % and the share of secondary copper is 44 % (KBOB et al. 2016). A recycling efficiency of 100 % was assumed for metals.

The life cycle inventory of the potential environmental benefits gained by recovered materials from recycled c-Si PV modules is presented in Tab. 3.4.

Tab. 3.4 Life cycle inventory of the avoided burdens due to materials recovered from used c-Si PV modules in a first generation recycling process according to the end-of-life approach.

	Name	Location	InfrastructureProcess	Unit	avoided burden from recycling, c-Si PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER			
	InfrastructureProcess				0			
	Unit				kg			
product	avoided burden from recycling, c-Si PV module	RER	0	kg	1			
technosphere	natural gas, burned in industrial furnace >100kW	RER	0	MJ	-8.82E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-5.71E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016
	silica sand, at plant	DE	0	kg	-3.73E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016
	soda, powder, at plant	RER	0	kg	-1.48E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016
	limestone, milled, packed, at plant	CH	0	kg	-2.58E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016
	copper, at regional storage	RER	0	kg	-3.09E-2	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary copper production materials from junction box and cables; Recycling content of copper is 44 % according to KBOB-list; Average based on information from two German recyclers; Ecoinvent v2.2:2016
	copper, secondary, at refinery	RER	0	kg	3.09E-2	1	1.14	(2,4,1,1,3,BU:1.05); Efforts for making secondary copper from scrap;
	aluminium, primary, at plant	RER	0	kg	-4.57E-2	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary aluminium production materials from frame; Recycling content of AlMg3 alloy is 77 % according to KBOB-list; Average based on information from two German recyclers; Ecoinvent v2.2:2016
	aluminium, secondary, from old scrap, at plant	RER	0	kg	4.57E-2	1	1.14	(2,4,1,1,3,BU:1.05); Efforts for making secondary aluminium from scrap;
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.34E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Average based on information from two German recyclers; Held and Ilg 2011; Ecoinvent v2.2:2016

3.3 CdTe PV modules

3.3.1 Description of the process

The weight of CdTe PV modules is approximately 16.5 kg/m^2, whereof about 96 % is glass (Stolz et al. 2016). The life cycle inventory of the recycling of unframed CdTe PV modules represents first generation technology at First Solar in Germany and was previously published by Sinha et al. (2012).

The average transport distance from the place of installation to the recycling plant is 678 km. At the recycling facility, the used CdTe PV modules are shredded and milled in a first step. The semiconductor film is then removed and dissolved for solid-liquid separation. Unrefined semiconductor material, which is composed of cadmium sludge and copper telluride cement, is recovered after the process steps precipitation and dewatering. The wet process requires the chemicals hydrogen peroxide, sodium hydroxide, sulphuric acid and deionised water and causes cadmium emissions to air and water. The yield of unrefined semiconductor is 0.0037 kg/kg. In addition, the bulk materials glass cullets and copper are recovered from CdTe PV module recycling. The total electricity demand is 0.265 kWh/kg and is covered by the German electricity mix (Sinha et al. 2012).

A small amount of waste plastic (0.037 kg/kg) and inert glass waste (0.008 kg/kg) is disposed of in municipal waste incineration plants and inert material landfills, respectively (Sinha et al. 2012).

3.3.2 Cut-off approach

The total efforts of CdTe PV module recycling are allocated economically to the co-products waste treatment, glass cullets, aluminium scrap, cadmium sludge and copper telluride cement by using the allocation factors listed in Tab. 3.5. The shares of the individual material fractions were determined based on information from First Solar[2]. The price of CdTe PV module treatment is approximately 0.040 USD/W (de Jong 2013), which corresponds to 0.298 EUR/kg when assuming a PV module efficiency of 140 W/m^2 (FirstSolar 2014) and a currency exchange rate of 1.14 USD/EUR (EUWID 2016). In general, the prices of all recovered materials exhibit high volatility. The price of glass cullets was estimated by Karsten Wambach[1] and the price of aluminium scrap was taken from EUWID (2016). The prices of recovered semiconductor precursors, cadmium sludge and copper telluride cement, were estimated based on information from USGS (2016a; 2016b) by assuming that they are valued at approximately 10 % the price of the pure value of the contained metals[3] (Classen et al. 2009).

Tab. 3.5 Mass fractions and prices used to calculate economic allocation factors for the cut-off modelling approach of CdTe PV module recycling (Sinha et al. 2012; de Jong 2013; EUWID 2016; USGS 2016a; USGS 2016b; Classen et al. 2009; personal communication Parikhit Sinha, First Solar, 06.10.2014 and 13.06.2016; personal communication Karsten Wambach, Wambach-Consulting, 15.06.2016).

CdTe recycling	Mass fraction (-)	Price	Allocation factor
	-	EUR/kg	-
Treatment	1.000	0.298	**0.847**
Glass cullets	0.963	0.020	**0.055**
Copper scrap	0.005	4.000	**0.054**
Cadmium sludge	0.002	0.092	**0.000**
Copper telluride cement	0.002	7.807	**0.043**

The life cycle inventories of CdTe PV module recycling according to the cut-off modelling approach are presented in Tab. 3.6. The major part of the recycling efforts is allocated to the waste treatment.

[2] Personal communication Parikhit Sinha, First Solar, 06.10.2014.

[3] Personal communication Parikhit Sinha, First Solar, 13.06.2016.

Tab. 3.6 Life cycle inventory of the treatment of used CdTe PV modules in a first generation recycling process and of the recovered materials according to the cut-off approach.

	Name	Location	InfrastructureProcess	Unit	treatment, CdTe PV module	glass cullets, recovered from CdTe PV module treatment	copper scrap, recovered from CdTe PV module treatment	cadmium sludge, recovered from CdTe PV module treatment	copper telluride cement, recovered from CdTe PV module treatment	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE	DE	DE	DE	DE			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
product	treatment, CdTe PV module	DE	0	kg	1	0	0	0	0			
	glass cullets, recovered from CdTe PV module treatment	DE	0	kg	0	1	0	0	0			
	copper scrap, recovered from CdTe PV module treatment	DE	0	kg	0	0	1	0	0			
	cadmium sludge, recovered from CdTe PV module treatment	DE	0	kg	0	0	0	1	0			
	copper telluride cement, recovered from CdTe PV module treatment	DE	0	kg	0	0	0	0	1			
technosphere	electricity, medium voltage, at grid	DE	0	kWh	2.24E-1	1.51E-2	3.02E+0	6.95E-2	5.89E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	water, deionised, at plant	CH	0	kg	2.78E-1	1.87E-2	3.74E+0	8.60E-2	7.29E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	sulphuric acid, liquid, at plant	RER	0	kg	4.28E-3	2.87E-4	5.75E-2	1.32E-3	1.12E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	2.93E-2	1.97E-3	3.94E-1	9.07E-3	7.68E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	5.34E-3	3.59E-4	7.18E-2	1.65E-3	1.40E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	transport, lorry >16t, fleet average	RER	0	tkm	5.75E-1	3.86E-2	7.72E+0	1.78E-1	1.51E+1	1	2.09	(4,5,na,na,na,na,BU:2); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	2.46E-4	1.65E-5	3.30E-3	7.61E-5	6.45E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	3.16E-2	2.12E-3	4.25E-1	9.78E-3	8.29E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	6.59E-3	4.43E-4	8.86E-2	2.04E-3	1.73E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
emission air, unspecified	Cadmium	-	-	kg	3.02E-10	2.03E-11	4.06E-9	9.35E-11	7.93E-9	1	5.02	(2,4,1,1,1,3,BU:5); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
emission water, unspecified	Cadmium, ion	-	-	kg	4.58E-9	3.08E-10	6.15E-8	1.42E-9	1.20E-7	1	3.02	(2,4,1,1,1,3,BU:3); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining

3.3.3 End-of-life approach

The takeback and recycling of CdTe PV modules and the potentially avoided burdens due to recovered materials are considered separately in the end-of-life approach. The life cycle inventory of first generation CdTe PV module takeback and recycling is shown in Tab. 3.7.

Tab. 3.7 Life cycle inventory of the takeback and recycling of used CdTe PV modules in a first generation recycling process according to the end-of-life approach.

	Name	Location	InfrastructureProcess	Unit	takeback and recycling, CdTe PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE			
	InfrastructureProcess				0			
	Unit				kg			
product	takeback and recycling, CdTe PV module	DE	0	kg	1			
technosphere	electricity, medium voltage, at grid	DE	0	kWh	2.65E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	water, deionised, at plant	CH	0	kg	3.28E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	sulphuric acid, liquid, at plant	RER	0	kg	5.05E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	hydrogen peroxide, 50% in H2O, at plant	RER	0	kg	3.46E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	6.31E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	transport, lorry >16t, fleet average	RER	0	tkm	6.78E-1	1	2.09	(4,5,na,na,na,na,BU:2); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	treatment, PV cell production effluent, to wastewater treatment, class 3	CH	0	m3	2.90E-4	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	3.73E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	7.78E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
emission air, unspecified	Cadmium	-	-	kg	3.57E-10	1	5.02	(2,4,1,1,1,3,BU:5); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining
emission water, unspecified	Cadmium, ion	-	-	kg	5.40E-9	1	3.02	(2,4,1,1,1,3,BU:3); ; Sinha: End-of-Life CdTe PV Recycling with Semiconductor Refining

The potential environmental benefits of recovered materials gained from CdTe PV module recycling were calculated by the same procedure as applied to c-Si PV modules (see section 3.2.3). Glass cullets replace the input materials of glass production (silica sand, soda powder and limestone), decrease the energy demand of the process (savings in the consumption of natural gas and heavy fuel oil) and prevent geogenic carbon dioxide emissions. Copper scrap yields credits for primary copper and in turn requires the production of secondary copper. The recovered unrefined semiconductor material results in avoided consumption of cadmium sludge and copper telluride cement.

The life cycle inventory of the potential environmental benefits gained by recovered materials from recycled CdTe PV modules is presented in Tab. 3.8.

Tab. 3.8 Life cycle inventory of the avoided burdens due to materials recovered from used CdTe PV modules in a first generation recycling process according to the end-of-life approach.

	Name	Location	InfrastructureProcess	Unit	avoided burden from recycling, CdTe PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				DE			
	InfrastructureProcess				0			
	Unit				kg			
product	avoided burden from recycling, CdTe PV module	DE	0	kg	1			
technosphere	natural gas, burned in industrial furnace >100kW	RER	0	MJ	-1.19E+0	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-7.67E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016
	silica sand, at plant	DE	0	kg	-5.01E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016
	soda, powder, at plant	RER	0	kg	-1.98E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016
	limestone, milled, packed, at plant	CH	0	kg	-3.47E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016
	copper, at regional storage	RER	0	kg	-2.68E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary copper production materials from junction box; Recycling content of copper is 44 % according to KBOB-list; Personal communication Parikhit Sinha, 06.10.2014; Ecoinvent v2.2:2016
	copper, secondary, at refinery	RER	0	kg	2.68E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Efforts for making secondary copper from scrap; Personal communication Parikhit Sinha, 06.10.2014
	cadmium sludge, from zinc electrolysis, at plant	GLO	0	kg	-1.72E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012: End-of-Life CdTe PV Recycling with Semiconductor Refining
	copper telluride cement, from copper production	GLO	0	kg	-1.95E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012: End-of-Life CdTe PV Recycling with Semiconductor Refining
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.80E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; Ecoinvent v2.2:2016

4 Life cycle impact assessment

4.1 Overview

A comparison of the environmental impacts caused by the treatment of used PV modules and the production of the PV systems based on the life cycle inventories according to the cut-off modelling approach is drawn in subchapter 4.2. The life cycle inventories according to the end-of-life modelling approach can be applied to estimate the net environmental impacts of PV module recycling (subchapter 4.3). The methodology of the analyses is shortly introduced for both modelling approaches and followed by a separate presentation and discussion of the results for c-Si and CdTe PV modules.

4.2 Cut-off approach: Environmental impacts of PV module treatment

4.2.1 Description of the PV system

The life cycle inventories of PV module recycling according to the cut-off modelling approach can be used to complement existing life cycle inventory data on PV systems. The relevance of the treatment of used c-si PV modules is assessed by considering a 3 kWp PV system mounted on a slanted rooftop, which is described in detail in Stolz et al. (2016). The PV system analysed encompasses the production of the PV modules, the mounting structure and the electric installation as well as the transport of the components to the place of installation and the installation itself. The inverter is not included in this analysis and the environmental impacts during the use phase are neglected. The end-of-life treatment of PV modules does not include the disposal of the mounting structure and the electric installation, which is accounted for in the production of the system (Jungbluth et al. 2012). The transport efforts of the mounting structure and the electric installation from the place of installation to the recycling plant are thus not taken into account.

The most relevant processes contributing to the environmental impacts of PV module recycling do not differ between the two modelling approaches and are distinguished in subchapter 4.3.

4.2.2 c-Si PV modules

The environmental impacts of the production of a c-Si PV system were calculated as the weighted average of multi- and monocrystalline Si PV modules, determined as the share of each technology in the total installed capacity in Europe. As can be seen from Tab. 4.1, the treatment of used c-Si PV modules causes a very small share in the total environmental impacts of a 3 kWp PV system mounted on a slanted roof according to the analysed environmental indicators. The highest contribution of the recycling effors

(0.8 %) is observed for the climate change impacts. Even if all impacts are allocated to the treatment of PV panels, this share stays well below 2 %.

Tab. 4.1 Environmental impacts of the production and first generation treatment of a 3 kWp c-Si PV system mounted on a slanted rooftop per kg PV module. The treatment of used PV modules is based on the life cycle inventory according to the cut-off modelling approach and does not include the disposal of the mounting structure and the electric installation. The environmental impacts of production were taken from a previous study (Stolz et al. 2016).

3 kWp c-Si PV system, mounted on a slanted roof		**Production**	**Treatment**	**Total**	***Treatment***
		kg PV module			***% of Total***
Particulate matter	kg PM2.5 eq	3.75E-02	**3.98E-05**	3.75E-02	*0.1%*
Freshwater ecotoxicity	CTUe	3.89E+01	**2.07E-01**	3.91E+01	*0.5%*
Human toxicity, non-cancer effects	CTUh, n-c	4.54E-06	**1.05E-08**	4.55E-06	*0.2%*
Human toxicity, cancer effects	CTUh, c	4.98E-07	**1.62E-09**	5.00E-07	*0.3%*
Mineral, fossil & renew. resources	kg Sb eq	6.18E-03	**4.43E-07**	6.18E-03	*0.0%*
Climate change	kg CO2 eq	2.72E+01	**2.29E-01**	2.74E+01	*0.8%*

4.2.3 CdTe PV modules

The results presented in Tab. 4.2 show that the treatment of used CdTe PV modules causes a small share in the total environmental impacts of a 3 kWp PV system mounted on a slanted roof according to the analysed environmental indicators. The contribution of CdTe PV module treatment is highest for the indicators climate change (4.3 %), human toxicity cancer effects (3.2 %) and particulate matter (2.3 %).

Tab. 4.2 Environmental impacts of the production and first generation treatment of a 3 kWp CdTe PV system mounted on a slanted rooftop per kg PV module. The treatment of used PV modules is based on the life cycle inventory according to the cut-off modelling approach and does not include the disposal of the mounting structure and the electric installation. The environmental impacts of production were taken from a previous study (Stolz et al. 2016).

3 kWp CdTe PV system, mounted on a slanted roof		**Production**	**Treatment**	**Total**	***Treatment***
		kg PV module			***% of Total***
Particulate matter	kg PM2.5 eq	3.20E-03	**7.56E-05**	3.27E-03	*2.3%*
Freshwater ecotoxicity	CTUe	1.96E+01	**1.32E-01**	1.97E+01	*0.7%*
Human toxicity, non-cancer effects	CTUh, n-c	1.30E-06	**1.86E-08**	1.32E-06	*1.4%*
Human toxicity, cancer effects	CTUh, c	1.98E-07	**6.59E-09**	2.05E-07	*3.2%*
Mineral, fossil & renew. resources	kg Sb eq	1.74E-03	**1.22E-06**	1.74E-03	*0.1%*
Climate change	kg CO2 eq	5.79E+00	**2.60E-01**	6.05E+00	*4.3%*

4.3 End-of-life approach: Net environmental impacts of PV module recycling

4.3.1 Definition of net environmental benefits

The net environmental benefits are calculated as the difference between the environmental impacts caused by the recycling of PV modules and the avoided burdens due to recovered materials. Negative numbers indicate that the recycling process yields net environmental benefits, implying that the environmental impacts of producing primary materials are higher compared to those caused by the PV recycling process. The results in the following sections are normalized to the environmental impacts of module treatment, which has net environmental impacts equal to 1.

4.3.2 c-Si PV modules

The first generation recycling of c-Si PV modules results in net environmental benefits according to all of the indicators analysed (Tab. 4.3). The potential benefits in the impact category mineral, fossil and renewable resource depletion are 58 times higher than the impacts caused by the recycling of c-Si PV modules. High net environmental benefits also result according to the indicators human toxicity cancer and non-cancer effects as well as particulate matter (-10, -9.1 and -6.8, respectively).

Tab. 4.3 Net environmental impacts of the first generation recycling of c-Si PV modules according to the end-of-life modelling approach. Results are normalized to the impacts of module treatment (=1; negative values: net benefits).

Impact category	c-Si
Particulate matter	-6.8
Freshwater ecotoxicity	-1.6
Human toxicity, non-cancer effects	-9.1
Human toxicity, cancer effects	-10
Mineral, fossil & renew. resources	-58
Climate change	-0.47

The relative contributions of the recovered materials in the potential benefits and the shares of the processes in the environmental impacts are shown in Fig. 4.1. The potential benefits due to recovered copper have the highest impact in the indicators mineral, fossil and renewable resource depletion, human toxicity non-cancer effects and freshwater ecotoxicity (Fig. 4.1, left). The indicator particulate matter is influenced by copper, glass and aluminium. The avoided burdens of aluminium recovery have a high contribution to cancer effects in humans, which is mainly due to chromium (VI) emissions to water in the production of primary aluminium. Both glass and aluminium recovery account for the potential benefits in climate change impacts. The production of secondary aluminium causes higher impacts than primary aluminium in the indicators human toxicity non-cancer effects and mineral, fossil and renewable resource depletion, which is due to zinc used as alloying element.

The environmental impacts according to the indicators particulate matter potential and mineral, fossil and renewable resource depletion of c-Si PV panel recycling are mainly caused by transport of the used panels to the recycling facility and by electricity supply (Fig. 4.1, right). The freshwater ecotoxicity impacts are strongly influenced by the disposal of plastics waste in municipal waste incineration plants and inert material landfills. Waste disposal is also responsible for the major part of climate change impacts, but also the electricity supply (recycling process) and the transport efforts have significant contributions. Human toxicity (cancer and non-cancer) effects are caused to a similar degree by all processes.

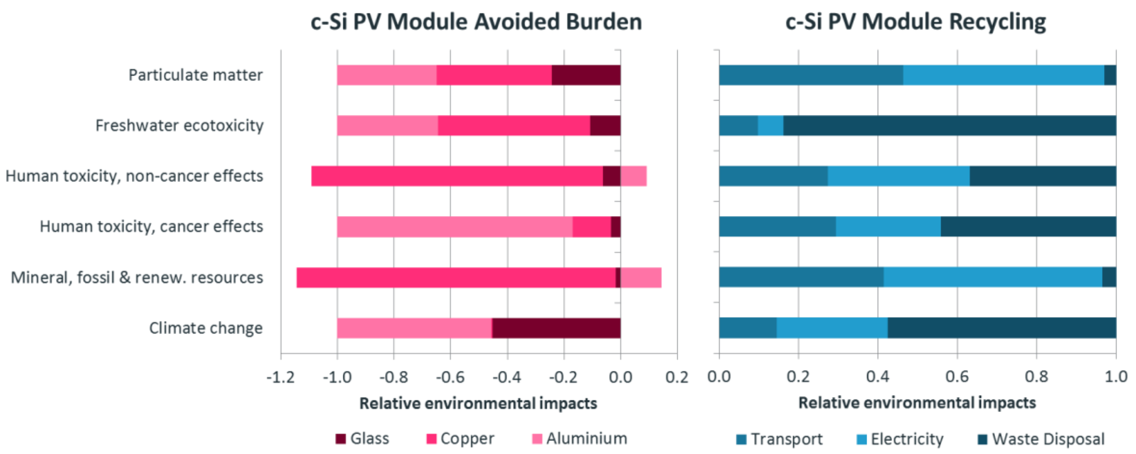

Fig. 4.1 Relative contributions of recovered materials to the potential benefits *(left)* and relative contributions of the treatment processes to the environmental burdens *(right)* of first generation c-Si PV module recycling.

4.3.3 CdTe PV modules

The first generation recycling of CdTe PV modules results in net environmental benefits according to five of the six indicators analysed (Tab. 4.4). The potential benefits in the impact category mineral, fossil and renewable resource depletion are 960 times higher than the impacts caused by the recycling of CdTe PV modules. In the other environmental indicators (except human toxicity, cancer effects), the net environmental benefits are much lower. The avoided environmental burdens by recovered materials do not outweigh the human toxicity, cancer effects, caused by the recycling efforts. These impacts are mainly caused by the use of hydrogen peroxide in the recycling process.

Tab. 4.4 Net environmental impacts of the first generation recycling of CdTe PV modules according to end-of-life modelling approach. Results are normalized to the impacts of module treatment (=1; negative values: net benefits).

Impact category	CdTe
Particulate matter	-1.8
Freshwater ecotoxicity	-0.65
Human toxicity, non-cancer effects	-1.8
Human toxicity, cancer effects	0.69
Mineral, fossil & renew. resources	-960
Climate change	-0.42

The relative contributions of the recovered materials in the potential benefits and the shares of the processes in the environmental impacts are shown in Fig. 4.2. The avoided burdens in the impact categories climate change, particulate matter, human toxicity cancer effects and freshwater ecotoxicity are mainly due to glass recovery (Fig. 4.2, left). Human toxicity, non-cancer effects, are influenced by the recovery of semiconductor, copper and glass. The indicator mineral, fossil and renewable resource depletion, which exhibits the highest potential net benefit (Tab. 4.4), is dominated by the recovery of semiconductor material.

The indicators particulate matter, human toxicity non-cancer effects and mineral, fossil and renewable resource depletion are influenced by transport of waste CdTe PV modules, electricity supply and the use of auxiliary materials (Fig. 4.2, right). The auxiliary materials, which are required for the dissolution of the semiconductor material, cause a high contribution to human toxicity, cancer effects, and to a lower degree to freshwater ecotoxicity. Disposal of waste materials is negligible compared to the total environmental impacts according to all indicators analysed.

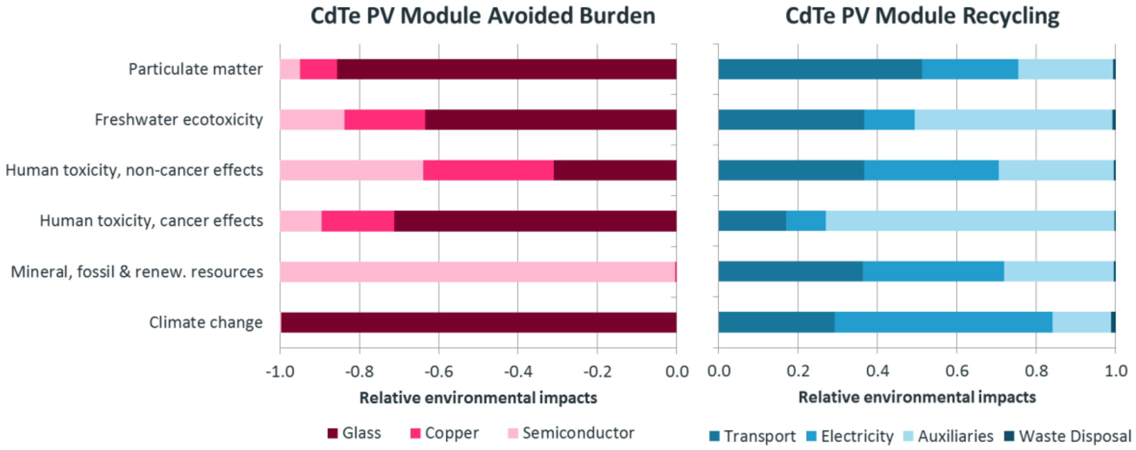

Fig. 4.2 Relative contributions of recovered materials to the potential benefits *(left)* and relative contributions of the treatment processes to the environmental burdens *(right)* of first generation CdTe PV module recycling.

5 Data quality and uncertainty

The data quality of the life cycle inventories of first generation c-Si PV module recycling is classified as satisfactory. The available data were obtained from two German recyclers and show significant difference in the specific electricity consumption. The transport distance to the recycling facility was estimated based on literature. The amounts of recovered materials are similar for both plants but the information available on the fate of the plastic material present in c-Si PV modules, which usually also contains the Si cell and precious metals such as silver, is inconclusive. According to the information obtained from the recycling companies, the plastic material is incinerated. However, there is some indication[4] that the plastic material is sometimes used as a substitute fuel and increasingly processed further for the recovery of other materials. These processes rather belong to second generation recycling of c-Si PV modules and are not addressed in the present study. It is recommended to continue compiling data on c-Si PV module recycling in order to make the data basis of the life cycle inventories more robust.

The data quality of the recycling efforts and the recovered materials of CdTe PV module recycling can be judged as very good. Detailed information about the recycling process is publicly available. The life cycle inventories of CdTe PV module recycling are therefore specific for First Solar's recycling facility located in Germany.

Another source of uncertainty, which is only relevant for the cut-off modelling approach, is the price of the treatment service and the recovered materials. This information is often classified as confidential by recycling companies. The high temporal variability in the price of recovered materials makes estimations difficult and increases the uncertainty.

Finally, the background data also contribute to the total uncertainty of the results. This becomes clear when considering the life cycle impact assessment results of c-Si PV module recycling according to the end-of-life approach. In the impact category human toxicity, cancer effects, the potential benefits are dominated by the avoided production of primary aluminium and the resulting avoided emissions of chromium (VI) to water. The use of secondary aluminium does not yield any environmental benefits compared to primary aluminium according to the indicators human toxicity, non-cancer effects, and mineral, fossil and renewable resource depletion, which is due to zinc used as an alloying element in the production of secondary aluminium. In both cases, the uncertainty in the life cycle inventories is difficult to estimate but this dominance of single substances should be acknowledged when interpreting the results.

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[4] Personal communication Karsten Wambach, Wambach-Consulting, 15.06.2016.

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