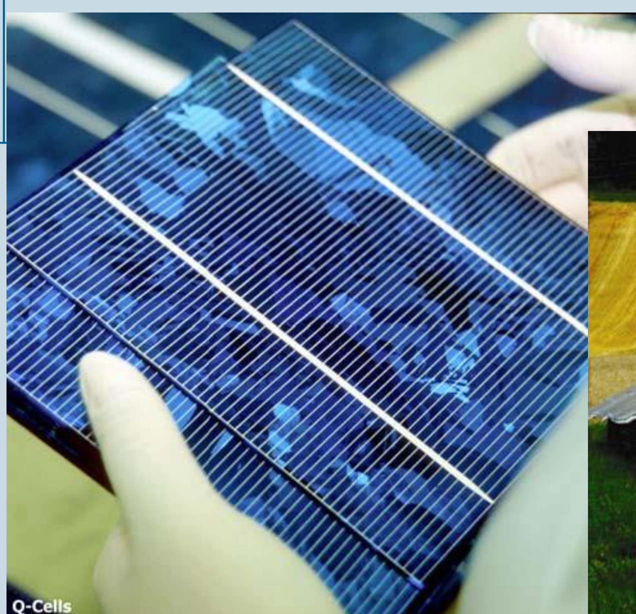
IEA INTERNATIONAL ENERGY AGENCY

Life Cycle Assessment of Current Photovoltaic Module Recycling



PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T12-13:2018

INTERNATIONAL ENERGY AGENCY PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Life Cycle Assessment of Current Photovoltaic Module Recycling

IEA PVPS Task 12, Subtask 2.0, LCA
Report IEA-PVPS T12-13:2018
ISBN 978-3-906042-69-5

December 2017

Operating agent:

Garvin Heath	National Renewable Energy Laboratory, USA

Authors:

Philippe Stolz	treeze Ltd., Switzerland
Rolf Frischknecht	treeze Ltd., Switzerland

Contributors:

Karsten Wambach	Wambach-Consulting, Germany
Parikhit Sinha	First Solar, USA
Garvin Heath	National Renewable Energy Laboratory, USA

Citation: *P. Stolz, R. Frischknecht, K. Wambach, P. Sinha, G. Heath, 2017, Life Cycle Assessment of Current Photovoltaic Module Recycling, IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12-13:2018.*

Abbreviations and Acronyms

a	year (annum)
BOS	balance of system
CdTe	cadmium telluride
CH	Switzerland
c-Si	crystalline silicon
ENTSO-E	European Network of Transmission System Operators for Electricity
EUR	euro
GLO	global average
IEA	International Energy Agency
KBOB	Coordination Group for Construction and Property Services (Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
MJ	megajoule
PEF	product environmental footprint
PEFCR	product environmental footprint category rule
PV	photovoltaic
PVPS	photovoltaic power systems
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 nineteen eighties and nineties reaching the end of their 30 year lifespan, their proper end of life treatment gets into focus. This report deals with the approaches, 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 crystalline silicon (c-Si) and cadmium telluride (CdTe) PV modules is described. Due to the still limited waste stream today, 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. 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 current c-Si and CdTe PV modules are compiled following two modelling approaches related to recycling. The cut-off approach uses economic allocation to divide the total efforts of the recycling process between 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 inventories of c-Si PV module recycling are based on data obtained from four European recyclers surveyed between 2015 and 2016. For CdTe PV module recycling, the life cycle inventories were established based on published data for the First Solar recycling facility in Germany. 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 1.1 %) compared to the impacts caused by the production of a 3 kWp residential 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 (4.8 %).

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 fair since only limited information is available. In contrast, the data quality of CdTe PV module recycling is considered very good.

The study was financed by the Swiss Federal Office of Energy (SFOE) and carried out in the framework of the Task 12 of the Photovoltaic Powers System Programme (PVPS) of the International Energy Agency (IEA).

Foreword

The IEA PVPS is one of the collaborative R&D Agreements established within the IEA, and was established in 1993. The overall programme is headed by an Executive Committee composed of representatives from each participating country and/or organisation, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By early 2015, fifteen Tasks were established within the PVPS programme, of which six are currently operational.

The IEA PVPS Implementing Agreement presently has 29 members and covers the majority of countries active in photovoltaics, both in R&D, production and installation. The programme deals with the relevant applications of photovoltaics, both for on-grid and off-grid markets. It operates in a task-shared mode whereby member countries and/or organisations contribute with their experts to the different Tasks. The co-operation deals with both technical and non-technical issues relevant to a wide-spread use of photovoltaics in these different market segments.

The mission of the IEA PVPS programme is: “To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” The underlying assumption is that the market for PV systems is rapidly expanding to significant penetrations in grid-connected markets in an increasing number of countries, connected to both the distribution network and the central transmission network. At the same time, the market is gradually shifting from a policy to a business driven approach.

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV growth to levels enabling it to make a major contribution to the needs of the member countries and the world.

The overall objectives of Task 12 are to accomplish the following:

1. Quantify the environmental profile of PV in comparison to other energy technologies;
2. Define and address environmental health & safety and sustainability issues that are important for market growth.

The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material-, and emission-flows in all the stages of the life of PV. The second objective will be addressed by assisting the collective action of PV companies in defining material availability and product-recycling issues, and on communicating “lessons learned” from incidents or potential ones in PV production facilities. A third objective (i.e., dissemination) will be accomplished by presentations to broad audiences, producing simple fact sheets documented by comprehensive reports, and engaging industrial associations and the media in the spreading this information.

Within Task 12, there are three targets of Subtask 2.0 “Life Cycle Assessment”: To quantify the environmental profile of electricity produced with PV systems (compared to that from other sources); to show trends in the improvement of PV's environmental profile; and, to assess this profile with the help of "external" costs, and other life-cycle-impact assessment methods.

Task 12 was initiated by Brookhaven National Laboratory under the auspices of the U.S. Department of Energy and is now operated jointly by the National Renewable Energy Laboratory (NREL) and Energy Center of the Netherlands (ECN). Support from DOE and ECN are gratefully acknowledged. Further information on the activities and results of the Task can be found at: http://www.iea-pvps.org.

Content

List of Figures

List of Tables

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 inventory data 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. According to the Product Environmental Footprint Category Rules (PEFCR) for PV electricity, approximately 95 % of c-Si PV modules are framed whereas the share of framed CdTe PV modules is negligible (Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation" 2016).

The balance of system components (e.g., 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 (including disposed materials) 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 in order to attribute the environmental impacts based on their contribution to the total economic value. The cut-off modelling 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*
  Under this 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 adding 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; 2017). However, in contrast to the PEF methodology where the potential benefits are shared between the recyclable material and the secondary material, the approach applied in this study fully allocates the potential benefits to the recyclable material (100/0 allocation). This allocation is suited to quantify the overall net environmental impacts of the recycling process.

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 (published in the forthcoming: Wambach et al. 2018). The recycling companies were asked about information on their energy and material consumption and the amount of recovered material. The information provided by four responding recyclers was used to establish a life cycle inventory of first generation recycling of c-Si PV panels. Three of the four recycling plants taking part in the survey are specialised on laminated glass recycling; the fourth facility is specialised on metal recycling. The data obtained from a fifth recycler were not included in this study because they were measured at a pilot recycling line, which ceased operation in spring 2016. Since c-Si PV modules are currently not recycled in dedicated facilities (Weckend et al. 2016; Wambach & Sander 2015), the present life cycle inventory represents the recycling process in plants designed for laminated glass (e.g. from cars) and metals. The data of the four recyclers considered were weighted by the annual mass of c-Si PV modules reported to be treated in the most recent year.

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 linked to KBOB (Coordination Group for Construction and Property Services) life cycle inventory data DQRv2:2016 (KBOB et al. 2016a), which are based on ecoinvent data v2.2 (ecoinvent Centre 2010). This data source contains extensive updates on energy supply and material production datasets. It ensures methodological continuity with former versions of the ecoinvent database and it is used by the Swiss administration. The analyses were performed with SimaPro v8.4.0 (PRé Consultants 2017).

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:

- particulate matter,

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

These impact categories were identified in the PEF screening study (Stolz et al. 2016) and in the PEFCR (Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation" 2016) as most relevant for the generation of PV electricity. The selected impact category indicators also allow a comparison of the environmental impacts of the recycling of PV modules and the impacts of the production and operation of PV systems as reported in the PEF screening study (Stolz et al. 2016). 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 in 2012 as reported by Stolz et al. (2016). Based on a previous study (Latunussa 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, 7.5 ton lorry) and subsequently to the recycling facility (400 km, >16 ton lorry). On-site transportation of c-Si PV modules is accomplished with a four-wheel loader (0.065 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. The c-Si PV modules are mechanically treated, yielding the bulk materials glass cullets, aluminium scrap and copper scrap. The process flow diagram of the Maltha recycling plant in Belgium is shown as an example in Fig. 3.1. More details on the treatment of used c-Si PV modules in the four recycling plants that provided data can be found in Wambach, Heath and Libby (2018).

The weighted average electricity demand of the machines is 0.111 kWh/kg, with large differences among the four recycling plants (3 laminated glass recyclers, 1 metal recycler). The electricity demand is modelled with the European electricity mix (ENTSO-E: European Network of Transmission System Operators for Electricity) since c-Si PV modules are treated in numerous recycling plants across Europe. The mechanical recycling of c-Si PV modules does not require any auxiliary materials. The plastic material fraction (0.173 kg/kg) is disposed of in municipal incineration plants and to the lesser part in sanitary landfills. It is mainly composed of polymers and foils but usually also includes the c-Si cell and silver.

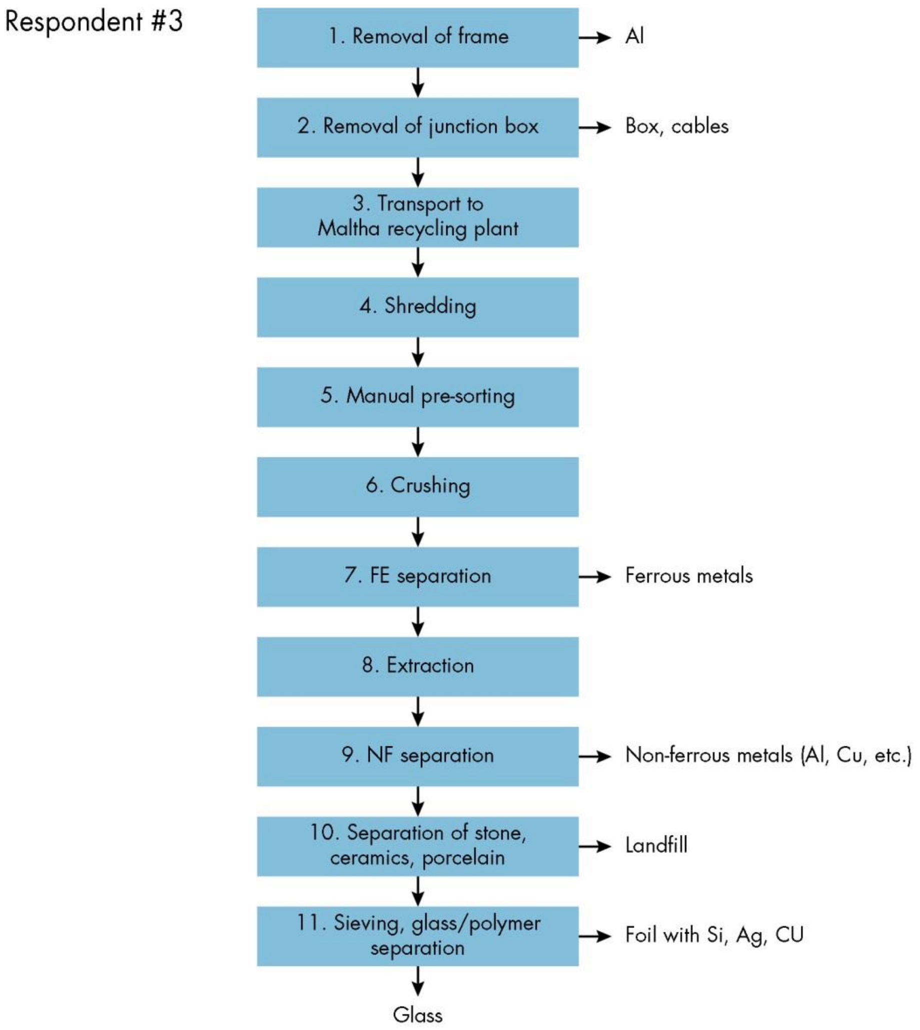


Fig. 3.1 Process flow diagram of the Maltha glass recycling plant in Belgium (Wambach et al. 2018). c-Si PV modules are treated mechanically in several process steps in order to recover the aluminium frame, the junction box, cables, ferrous and non-ferrous metals as well as glass.

3.2.2 Cut-off approach

When applying the cut-off approach, the total efforts of c-Si PV module recycling are allocated to the co-products waste treatment, glass cullets, aluminium scrap and copper scrap by using the economic 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 (Wambach et al. 2018). Two recyclers only reported the mass of non-ferrous metals recovered. In these cases, the shares of aluminium and copper in the total mass of non-ferrous metals were assumed to be the same as for the other recycling companies. The amounts of copper and aluminium recovered are significantly higher compared to their mass fractions in c-Si PV modules produced today (Weckend et al. 2016). This difference probably reflects historical changes in module composition since the major part of modules being recycled today were produced many years ago.

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). A large part of the recycling efforts is allocated to the waste treatment and the copper scrap.

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 and 11.08.2017; Brellinger 2014; EUWID 2016).

c-Si recycling	**Mass fraction (-)**	**Price**	**Allocation factor**
	-	**EUR/kg**	**-**
Treatment	1.000	0.275	**0.500**
Glass cullets	0.662	0.020	**0.024**
Aluminium scrap	0.121	0.700	**0.154**
Copper scrap	0.044	4.000	**0.322**

The life cycle inventories of c-Si PV module recycling according to the cut-off modelling approach are presented in Tab. 3.2.

1 Personal communication Karsten Wambach, Wambach-Consulting, 15.06.2016 and 11.08.2017.

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. Data were obtained from four recycling plants in Europe (3 laminated glass recyclers, 1 metal recycler).

	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	5.56E-2	4.05E-3	1.42E-1	8.09E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	diesel, burned in building machine	GLO	0	MJ	3.24E-2	2.36E-3	8.25E-2	4.71E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	7.34E-2	5.34E-3	1.87E-1	1.07E+0	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	1.28E-2	9.33E-4	3.26E-2	1.87E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers; Economic allocation;
	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	5.00E-2	3.64E-3	1.27E-1	7.27E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: 100 km; Economic allocation; Latunussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	2.00E-1	1.45E-2	5.09E-1	2.91E+0	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 400 km; Economic allocation; Latunussa 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.

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. Data were obtained from four recycling plants in Europe (3 laminated glass recyclers, 1 metal recycler).

	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	1.11E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers;
	diesel, burned in building machine	GLO	0	MJ	6.48E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers;
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	1.47E-1	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers;
	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	2.57E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Weighted average of data from recyclers;
	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: 100 km; Latunussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	4.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 400 km; Latunussa et al. 2016

The potential environmental benefits gained by recovered materials were calculated based on the methodology developed under the PEF Pilot process and applied in the PEF screening study (Stolz et al. 2016). A 100/0 allocation (i.e., the potential benefits are fully allocated to the recyclable material, no benefits are allocated to the secondary material) 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 (0.662 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 3 % when replacing 10 % of the input material by glass cullets. The recycling efficiency was estimated at 90 % (Sinha et al. 2012).

The aluminium scrap (0.121 kg/kg) is recovered from the frame of the c-Si PV module. In addition, copper scrap (0.044 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 (i.e., the share of primary material in the current supply mix that is displaced by recycled material; see also EN 15804 2013). According to KBOB life cycle inventory data DQRv2:2016 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. 2016b). 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. Data were obtained from four recycling plants in Europe (3 laminated glass recyclers, 1 metal recycler).

	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	-8.15E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-5.28E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	silica sand, at plant	DE	0	kg	-3.44E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	soda, powder, at plant	RER	0	kg	-1.36E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	limestone, milled, packed, at plant	CH	0	kg	-2.38E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	copper, at regional storage	RER	0	kg	-2.48E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary copper production materials from junction box and cables; Recycling content of copper is 44 % according to KBOB-list; Weighted average of data from recyclers; KBOB LCI data DQRv2:2016
	copper, secondary, at refinery	RER	0	kg	2.48E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); Efforts for making secondary copper from scrap;
	aluminium, primary, at plant	RER	0	kg	-5.34E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary aluminium production materials from frame; Recycling content of AlMg3 alloy is 77 % according to KBOB-list; Weighted average of data from recyclers; KBOB LCI data DQRv2:2016
	aluminium, secondary, from old scrap, at plant	RER	0	kg	5.34E-2	1	1.14	(2,4,1,1,1,3,BU:1.05); Efforts for making secondary aluminium from scrap;
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.24E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recyclers; Held and Ilg 2011; KBOB LCI data DQRv2:2016

3.3 CdTe PV modules

3.3.1 Description of the process

The average weight of CdTe PV modules produced between 2010 and 2011 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 (Sinha et al. 2012). It was assumed that the used PV modules are first transported to a collection point located 100 km from the place of installation by a 7.5 ton lorry. The subsequent transport to the recycling plant is then accomplished by a >16 ton lorry (Latunussa et al. 2016). At the recycling facility, the junction box is removed and the used CdTe PV modules are shredded and milled. The semiconductor film is then removed in a chemical process and dissolved for solid-liquid separation. Unrefined semiconductor material, which is composed of cadmium sludge and copper telluride cement, is recovered after precipitation and dewatering. The wet process requires the chemicals hydrogen peroxide, sodium hydroxide, sulphuric acid and deionised water and causes controlled cadmium emissions to air and water. The yield of unrefined cadmium telluride 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 since the CdTe PV module recycling facility operated by First Solar is located in Germany (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 to the co-products waste treatment, glass cullets, aluminium scrap, cadmium sludge and copper telluride cement by using the economic allocation factors listed in Tab. 3.5. The mass fractions of each material were determined based on information from First Solar[2]. The price of CdTe PV module treatment for the year 2013 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).

The glass cullets make up a large share of the recovered material and have a relatively low price. In contrast, the recovered mass of the more valuable materials copper scrap and copper telluride cement is much lower. In combination with the price of the CdTe PV module treatment, the resulting allocation factors of the recovered materials is low. 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. 3.5 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 and 11.08.2017).

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	**0.00045**
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.

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. Data are representative for the First Solar recycling facility in Germany (Sinha et al. 2012).

	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	8.47E-2	5.69E-3	1.14E+0	2.62E-2	2.22E+0	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: km; Sinha et al. 2012; Latanussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	4.90E-1	3.29E-2	6.59E+0	1.52E-1	1.29E+1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: km; Sinha et al. 2012; Latanussa et al. 2016
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
	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	(2,4,1,1,3,BU:1.05); ; Sinha et al. 2012
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 et al. 2012
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 et al. 2012

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. Data are representative for the First Solar recycling facility in Germany (Sinha et al. 2012).

	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 et al. 2012
	water, deionised, at plant	CH	0	kg	3.28E-1	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	sulphuric acid, liquid, at plant	RER	0	kg	5.05E-3	1	1.14	(2,4,1,1,1,3,BU:1.05); ; Sinha et al. 2012
	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 et al. 2012
	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 et al. 2012
	transport, lorry 3.5-7.5t, EURO5	RER	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to collection point: 100 km; Sinha et al. 2012; Latanussa et al. 2016
	transport, lorry >16t, fleet average	RER	0	tkm	5.78E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 400 km; Sinha et al. 2012; Latanussa et al. 2016
	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 et al. 2012
	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 et al. 2012
	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 et al. 2012
emission air, unspecified	Cadmium	-	-	kg	3.57E-10	1	5.02	(2,4,1,1,1,3,BU:5); ; Sinha et al. 2012
emission water, unspecified	Cadmium, ion	-	-	kg	5.40E-9	1	3.02	(2,4,1,1,1,3,BU:3); ; Sinha et al. 2012

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 avoiding production of primary copper and in turn requires the production of secondary copper. Benefits for recycling are granted only for the net surplus amount of recycled material, which leaves the PV system. 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. Data are representative for the First Solar recycling facility in Germany (Sinha et al. 2012).

	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	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-7.67E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	silica sand, at plant	DE	0	kg	-5.01E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	soda, powder, at plant	RER	0	kg	-1.98E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	limestone, milled, packed, at plant	CH	0	kg	-3.47E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016
	copper, at regional storage	RER	0	kg	-2.68E-3	1	1.14	(2,4,1,1,3,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; KBOB LCI data DQRv2:2016
	copper, secondary, at refinery	RER	0	kg	2.68E-3	1	1.14	(2,4,1,1,3,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	(2,4,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012
	copper telluride cement, from copper production	GLO	0	kg	-1.95E-3	1	1.14	(2,4,1,1,3,BU:1.05); Avoided unrefined semiconductor materials; Sinha et al. 2012
emission air, unspecified	Carbon dioxide, fossil	-	-	kg	-1.80E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Held and Ilg 2011; KBOB LCI data DQRv2:2016

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 to the total life cycle impacts of c-Si modules can be assessed by considering, for instance, a 3 kWp PV system mounted on a slanted rooftop, which is described in detail in Stolz et al. (2016). In this example, 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 efforts (1.1 %) is observed for the climate change impacts. Even if all impacts are allocated to the treatment of PV panels, this share stays well below 3 % (see allocation factors in Tab. 3.1).

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 (based on data from four European recyclers) 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	3.14E-02	**3.58E-05**	3.15E-02	*0.1%*
Freshwater ecotoxicity	CTUe	3.26E+01	**2.71E-01**	3.29E+01	*0.8%*
Human toxicity, non-cancer effects	CTUh, n-c	3.81E-06	**1.18E-08**	3.82E-06	*0.3%*
Human toxicity, cancer effects	CTUh, c	4.18E-07	**1.90E-09**	4.20E-07	*0.5%*
Mineral, fossil & renew. resources	kg Sb eq	5.17E-03	**4.88E-07**	5.17E-03	*0.0%*
Climate change	kg CO2 eq	2.28E+01	**2.56E-01**	2.30E+01	*1.1%*

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 (4.8 %), human toxicity cancer effects (3.4 %) and particulate matter (2.6 %).

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 (based on data for the First Solar recycling facility in Germany) 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	**8.37E-05**	3.28E-03	*2.6%*
Freshwater ecotoxicity	CTUe	1.96E+01	**1.54E-01**	1.97E+01	*0.8%*
Human toxicity, non-cancer effects	CTUh, n-c	1.30E-06	**2.20E-08**	1.32E-06	*1.7%*
Human toxicity, cancer effects	CTUh, c	1.98E-07	**7.01E-09**	2.05E-07	*3.4%*
Mineral, fossil & renew. resources	kg Sb eq	1.74E-03	**1.50E-06**	1.74E-03	*0.1%*
Climate change	kg CO2 eq	5.79E+00	**2.89E-01**	6.08E+00	*4.8%*

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 recycling, 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 54 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, -11 and -8.0, 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 based on data from four European recyclers. Results are normalized to the impacts of module recycling (=1; negative values: net benefits).

Impact category	c-Si
Particulate matter	-8.0
Freshwater ecotoxicity	-1.2
Human toxicity, non-cancer effects	-11
Human toxicity, cancer effects	-10
Mineral, fossil & renew. resources	-54
Climate change	-0.49

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 and human toxicity non-cancer effects (Fig. 4.1, left). 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 aluminium and glass recovery account for the potential benefits in climate change impacts. The avoided freshwater ecotoxicity impacts are mainly caused by substituting primary aluminium and copper by secondary materials. The indicator particulate matter is influenced by aluminium, copper and glass.

The environmental impacts of c-Si PV panel recycling according to the indicators particulate matter potential and mineral, fossil and renewable resource depletion are mainly caused by the 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 the climate change impacts, but also the transport efforts and the electricity supply (recycling process) significant contributions. Human toxicity (cancer and non-cancer) effects are mainly caused by waste disposal and transport.

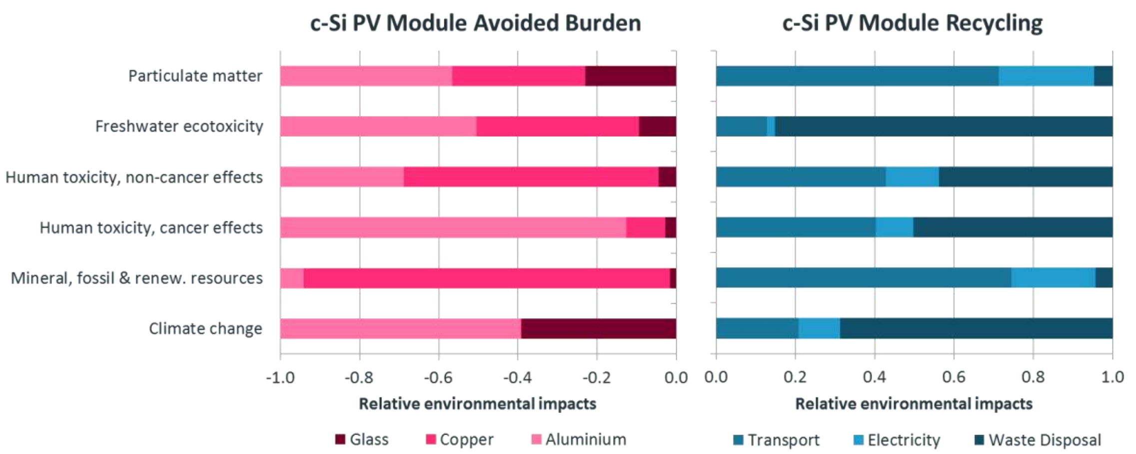


Fig. 4.1 Relative contributions of recovered materials to the potential benefits *(left)* and relative contributions of the recycling processes to the environmental burdens *(right)* of first generation c-Si PV module recycling based on data from four European recyclers.

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 750 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 based on data for the First Solar recycling facility in Germany. Results are normalized to the impacts of module recycling (=1; negative values: net benefits).

Impact category	CdTe
Particulate matter	-1.6
Freshwater ecotoxicity	-0.41
Human toxicity, non-cancer effects	-1.4
Human toxicity, cancer effects	0.71
Mineral, fossil & renew. resources	-750
Climate change	-0.28

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 to a similar degree 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 (modelled by the precursors cadmium sludge and copper telluride cement).

The indicators particulate matter, human toxicity non-cancer effects and mineral, fossil and renewable resource depletion are influenced by the 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 lesser extent to freshwater ecotoxicity. Disposal of waste materials is negligible compared to the total environmental impacts according to all indicators analysed.

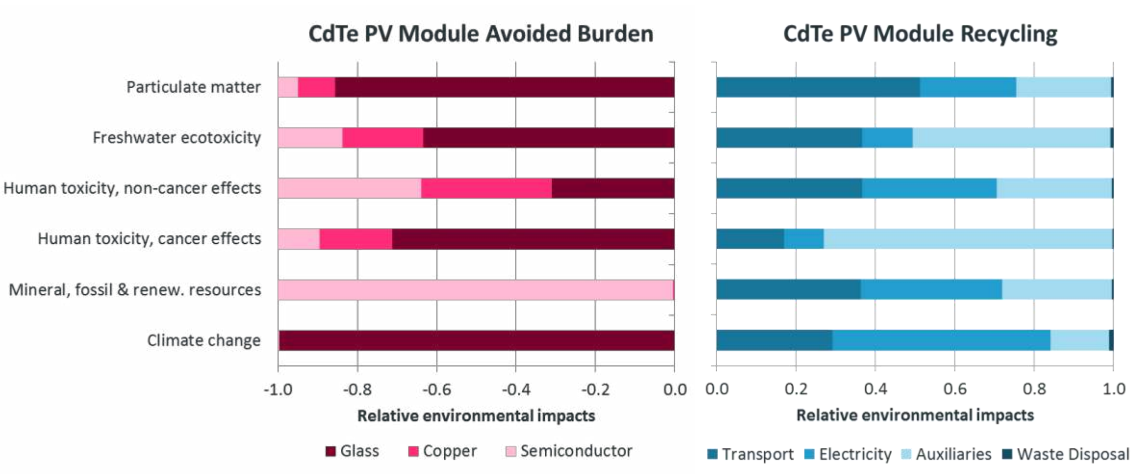


Fig. 4.2 Relative contributions of recovered materials to the potential benefits *(left)* and relative contributions of the recycling processes to the environmental burdens *(right)* of first generation CdTe PV module recycling based on data for the First Solar recycling facility in Germany.

5 Data quality and uncertainty

The data quality of the life cycle inventories of first generation c-Si PV module recycling is classified as fair. The available data were obtained from four European recyclers and show significant difference in the specific electricity consumption. This is partly due to the different specialisation of the recycling companies surveyed (three laminated glass recyclers and one metal recycler). There is also significant uncertainty in the estimation of electricity consumption because the recyclers did not have metering to measure the specific electricity consumption of the PV modules batch run. The transport distance to the recycling facility was estimated based on literature. The amounts of recovered materials are similar for all recycling plants but the information available on the fate of the plastic material present in c-Si PV modules, which usually also contains the 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 the second generation recycling technology 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.

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

References

Brellinger 2014 — Brellinger C. (2014) Cost for the Recycling and Registration of Solar Modules - a practical example. take-e-way GmbH, Hamburg, Germany.

Classen et al. 2009 — Classen M., Althaus H.-J., Blaser S., Doka G., Jungbluth N. and Tuchschmid M. (2009) Life Cycle Inventories of Metals. ecoinvent report No. 10, v2.1. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

de Jong 2013 — de Jong T. (2013) Manufacturing Update. First Solar, Inc.

ecoinvent Centre 2010 — ecoinvent Centre (2010) ecoinvent data v2.2, ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland, retrieved from: www.ecoinvent.org.

EN 15804 2013 — EN 15804 (2013) EN 15804:2012+A1:2013 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardisation (CEN), Brussels.

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.

European Commission 2013 — European Commission (2013) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union.

European Commission 2017 — European Commission (2017) PEFCR Guidance Document - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 2017. European Commission.

EUWID 2016 — EUWID (2016) Recycling und Entsorgung 18.2016. EUWID Europäischer Wirtschaftsdienst GmbH, Gernsbach, Germany.

FirstSolar 2014 — FirstSolar (2014) Key Quarterly Financial Data, retrieved from: http://investor.firstsolar.com/

Frischknecht et al. 2007 — Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Frischknecht 2010 — Frischknecht R. (2010) LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. In: Int J LCA, 15(7), pp. 666-671, retrieved from: DOI: 10.1007/s11367-010-0201-6.

Frischknecht et al. 2015	Frischknecht R., Itten R., Sinha P., de Wild Scholten M., Zhang J., Fthenakis V., Kim H. C., Raugei M. and Stucki M. (2015) Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. International Energy Agency (IEA) PVPS Task 12.
Held & Ilg 2011	Held M. and Ilg R. (2011) Update of environmental indicators and energy payback time of CdTe PV systems in Europe. In: PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS, 19, pp. 614-626.
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. 2016a	KBOB, eco-bau and IPB (2016a) 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.
KBOB et al. 2016b	KBOB, eco-bau and IPB (2016b) KBOB Ökobilanzdatenbestand DQRv2:2016; Grundlage für die KBOB-Empfehlung 2009/1:2016: Ökobilanzdaten im Baubereich, Stand 2016. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: www.lc-inventories.ch.
Kellenberger et al. 2007	Kellenberger D., Althaus H.-J., Jungbluth N., Künniger T., Lehmann M. and Thalmann P. (2007) Life Cycle Inventories of Building Products. ecoinvent report No. 7, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Latunussa et al. 2016	Latunussa C. E. L., Ardente F., Blengini G. A. and Mancini L. (2016) Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. In: Solar Energy Materials and Solar Cells, pp. 1-11, retrieved from: http://dx.doi.org/10.1016/j.solmat.2016.03.020.
PRé Consultants 2017	PRé Consultants (2017) SimaPro 8.4.0, Amersfoort, NL.
Sinha et al. 2012	Sinha P., Cossette M. and Ménard J.-F. (2012) End-of-Life CdTe PV Recycling with Semiconductor Refining. In: 27th European Photovoltaic Solar Energy Conference and Exhibition, pp. 4353-4356.
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.

Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation" 2016 Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation" (2016) Product Environmental Footprint Category Rules: Production of Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation (NACE/CPA class 27.90 “Manufacturing of other electrical equipment”).

USGS 2016a USGS (2016a) Cadmium. U.S. Geological Survey.

USGS 2016b USGS (2016b) Tellurium. U.S. Geological Survey.

Wambach & Sander 2015 Wambach K. and Sander K. (2015) Perspectives on Management of End-of-Life Photovoltaic Modules. In: 31st European Photovoltaic Solar Energy Conference and Exhibition, pp. 3073-3078.

Wambach et al. 2018 Wambach K., Heath G. and Libby C. (2018) Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe. IEA-PVPS Task 12 Report T12-12:2017.

Weckend et al. 2016 Weckend S., Wade A. and Heath G. (2016) End-of-Life-Management: Solar Photovoltaic Panels. IRENA and IEA-PVPS Task 12.

ISBN 978-3-906042-69-5

9 783906 042695 >