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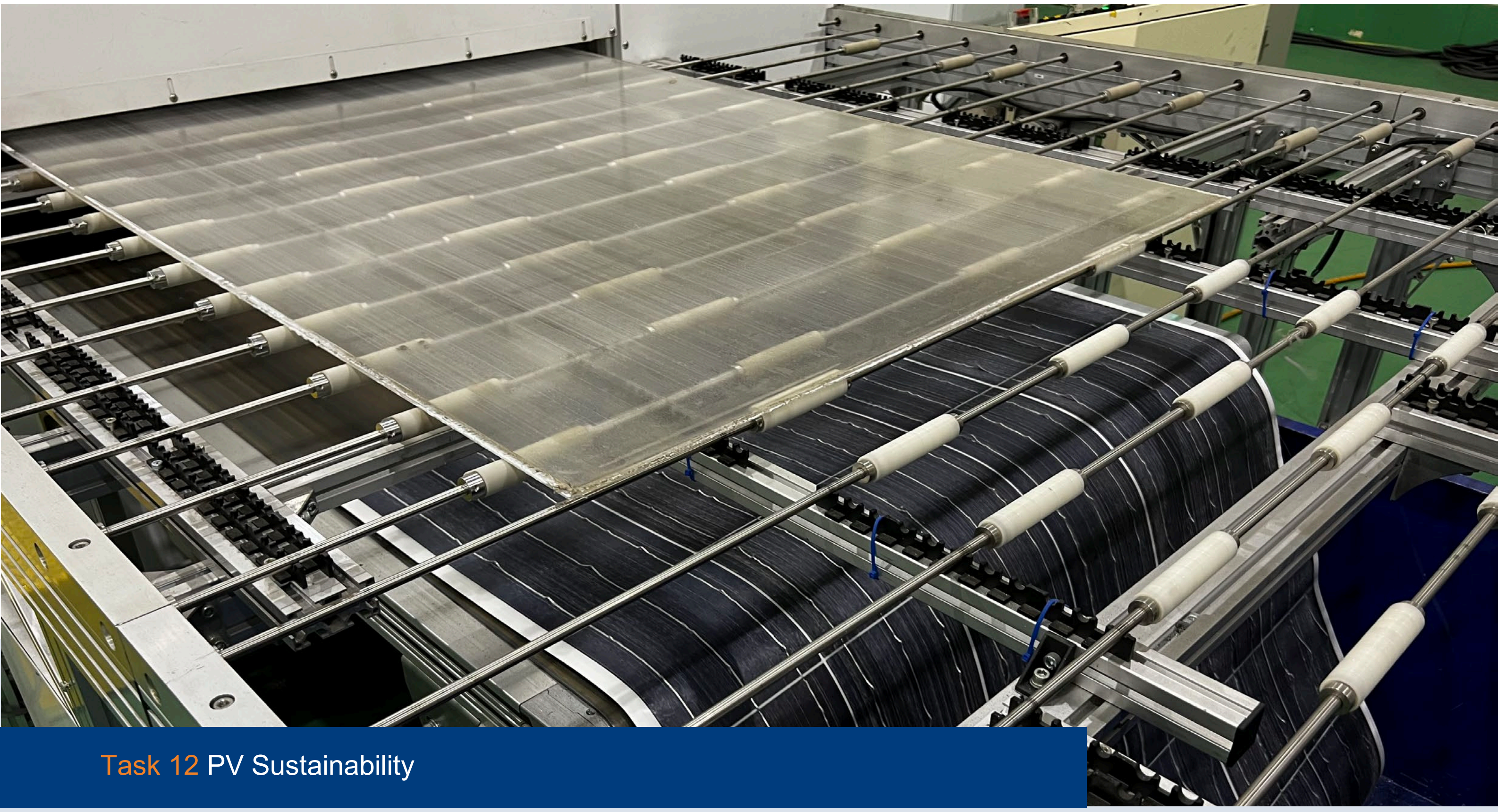

Task 12 PV Sustainability

PVPS

Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology
2023

Report IEA-PVPS T12-25:2023

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The program comprises experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (PVPS) is a TCP within the IEA; it was established in 1993. The mission of the program 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." To achieve this, the program's participants have undertaken a variety of joint research projects in photovoltaic (PV) power systems applications. The overall program is headed by an executive committee comprising one delegate from each country or organization member, which designates distinct "tasks," which may be research projects or activity areas.

The 25 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

Visit us at: www.iea-pvps.org.

What is IEA PVPS Task 12?

Task 12 aims to foster international collaboration in safety and sustainability that are crucial for ensuring that PV penetration increases to levels high enough to make a major contribution to the energy needs and emissions reductions of the member countries and the world. The overall objectives of Task 12 are to (1) quantify the environmental profile of PV compared to other energy technologies; (2) investigate end-of-life management options for PV systems as deployment increases and as older systems are decommissioned; and (3) define and address environmental health and safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments that describe the energy, material, and emissions flows in all stages of the life of PV. The second objective is addressed through the analysis of recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is jointly operated by the National Renewable Energy Laboratory and the University of New South Wales (UNSW Sydney). Support from the U.S. Department of Energy and the UNSW are gratefully acknowledged.

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COVER PICTURE: PV module recycling facility, courtesy of NPC Incorporated, Japan

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology

IEA PVPS
Task 12: PV Sustainability

Report IEA-PVPS T12-25:2023
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ACKNOWLEDGEMENTS

This report received valuable contributions from several International Energy Agency Photovoltaic Power Systems Programme Task 12 members as well as feedback from executive committee members that helped to further improve the contents.

LIST OF ABBREVIATIONS

c-Si	crystalline silicon
CH	Switzerland
EOL	end of life
EVA	ethylene vinyl acetate
IEA	International Energy Agency
ILCD	International Life Cycle Data System
KBOB	Coordination Group for Construction and Property Services (Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)
kWp	kilowatt peak
LCA	life cycle assessment
LCI	life cycle inventory
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PV	photovoltaic
PVPS	Photovoltaic Power Systems Programme
UVEK	Federal Department of the Environment, Transport, Energy and Communications (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation)

EXECUTIVE SUMMARY

The objective of this study is to complete a life cycle assessment (LCA) of a novel technology that separates the crystalline silicon (c-Si) photovoltaic (PV) module front glass from the backsheet using hot knife technology. This is known to be the most challenging step in module recycling, where the choice of delamination approach can determine the process selection for the next steps of the recycling process, the economic value of the recovered materials, and environmental performance.

The life cycle inventory (LCI) reported here is based on primary data from the technology manufacturer. Different LCIs are established following the cut-off approach and the end-of-life (EOL) approach. The environmental impacts of the hot knife delamination process are analysed based on six indicators, and the main contributors to delamination efforts are identified. For the EOL approach, the potential environmental benefits from the recovered materials are compared to the environmental impacts caused by the delamination process.

The functional unit of this analysis is the delamination of 1 kg of used framed c-Si PV modules at the place of installation.

A questionnaire was sent to the manufacturer of the hot knife technology. The manufacturer was asked to provide information on their energy and material consumption and the amount and quality of the recovered materials. The disclosed information was used to establish an LCI of the hot knife delamination of c-Si PV panels. The LCL represents the technology as used in a pilot plant; the data are representative of year 2018.

To complete the life cycle of c-Si PV, the production and installation of the PV system are represented by the International Energy Agency Photovoltaic Power Systems Program Task 12 LCI update 2020 database using the weighted average of multicrystalline and monocrystalline Si PV modules based on the share of the global installed capacity of each technology in 2018. For other processes, such as background processes for which no specific data were collected, the Federal Department of the Environment, Transport, Energy, and Communications (UVEK) LCI database DQRv2:2022 is used.

The hot knife delamination process of c-Si PV modules is automated in a PV module disassembly line that consists of a junction box (J-box) separator, a frame separator, and a glass separator (hot knife technology), and it involves the following three steps:

- Removal of the J-box, after which cables are removed from the separated J-box
- Removal of the aluminium frame
- Separation of the glass from the laminate backsheet.

The hot knife delamination technology is only one part of a high-value recycling process. After hot knife processing, the copper cables and the laminate (cell and ethylene vinyl acetate [EVA] backsheet) are sold to an external recycling facility (refinery) where the EVA plastic is burned and the copper and silver are recovered. Processing at the external recycling facility and the recovery of copper and silver are not considered within the system boundary of the LCA presented here, nor are potentially avoided emissions accounted for. Burdens of the three disassembly and delamination steps are shared between the treatment service (EOL processing of the PV module) and the materials and components that are recovered by following economic allocation principles (revenues).

We find that the hot knife treatment of decommissioned c-Si PV modules causes a very small share of the life cycle environmental impacts of a 3-kWp PV system mounted on a slanted roof in Europe, according to the analysed environmental indicators. The highest contribution of delamination is observed for the climate change impacts, mainly caused by transport logistics (module collection and delivery to the hot knife treatment site) and electricity consumption. Our findings are consistent with other literature; detailed comparisons of the environmental impacts of this delamination process to other approaches can be the subject of future research.

Further development of the process could increase the amount and diversity of the recovered materials—in particular, metals. Large-scale deployment of the process could also lead to lower energy and consumables use per panel treated based on process innovations.

We recommend compiling primary data on copper cable and laminate treatment and the recycling of copper and silver to make the data basis of the LCIs more complete and robust.

1 INTRODUCTION

1.1 Motivation and goal

The amount of photovoltaic (PV) modules that reach end of life (EOL) will increase in the years to come. In view of the increasing amounts of electronic waste that will beed to be treated, technical processes to recover precious and valuable resources available in EOL crystalline silicon (c-Si) PV modules are being developed.

A complete and high-value recycling process of c-Si PV modules involves disassembly (aluminium frame, junction box [J-box] with copper cables); delamination; and further processing to recover silicon and valuable metals, such as copper and silver, among others (Deng et al. 2022). The hot knife technology under assessment covers the disassembly and delamination steps but no further treatment processes that are operated by third parties.

Several delamination technologies are currently being developed and tested: mechanical, chemical mechanical crushing, mechanical high-voltage crushing, mechanical cutting, and mechanical peeling (Deng et al. 2022). Hot knife technology, a mechanical cutting technology, was developed in Japan and is currently operating in a pilot plant.

This report presents an life cycle assessment (LCA) on the environmental impacts of the treatment and recovery process and compares the environmental impacts attributed to the recovered materials to those of corresponding materials from primary sources.

1.2 Contents of this report

Chapter 2 describes the scope of the assessment, including the definition of the functional unit (Subchapter 2.1), the description of the PV system design (Subchapter 2.2), the allocation principles applied (Subchapter 2.3), the data sources used (Subchapter 2.4), and a description of the four resource use indicators (Subchapter 2.5). Chapter 3 contains a coarse description of the life cycle inventory (LCI) data used, including a table with the key characteristics and parameters of the PV systems and their supply chains. Chapter 4 contains the description and discussion of the cumulative resource use impacts and considerations regarding data quality and uncertainty. Chapter 5 discusses data quality, and Chapter 6 contains conclusions and gives future recommendations.

2 SCOPE

2.1 Objective

The objectives of this study are to compile LCIs of the delamination of c-Si PV modules using hot knife technology and to consider this first step of EOL treatment of c-Si PV modules in the context of manufacturing c-Si PV systems. Different LCIs are established following the cut-off approach and the EOL approach (see Subchapter 2.3). The environmental impacts of the PV module delamination process are analysed based on six indicators, and the main contributors to the delamination efforts are identified. For the EOL approach, the potential environmental benefits from the recovered materials are compared to the environmental impacts caused by the delamination process.

2.2 Functional unit

The functional unit of this analysis is the delamination of 1 kg of EOL framed c-Si PV modules at the place of installation.

The balance-of-system components (e.g., mounting structure and the electric installation required for PV systems) are not included in the LCIs of the delamination process nor are the potential benefits due to recycling because they are treated separately from the PV modules.

2.3 Modelling approaches

Different modelling approaches exist for recycling processes (Frischknecht 2010). The LCIs of c-Si PV module delamination were compiled according to two different approaches:

CUT-OFF APPROACH

The delamination efforts are economically allocated among the treatment process (including disposed materials) and all the recovered materials with a positive economic value, see Fig. 2.1. Economic allocation accounts for the mass fraction and the (relative) price of the coproducts 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 LCIs of PV systems.

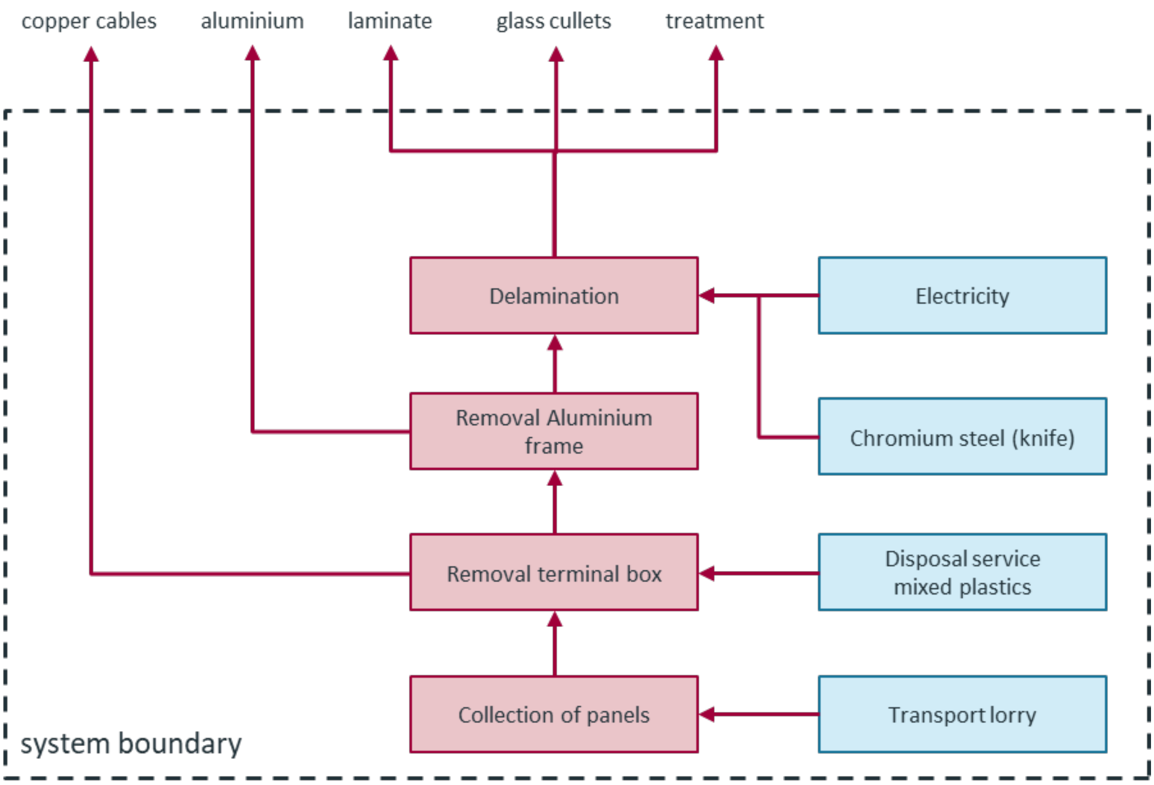

Fig. 2.1 System boundary and process outputs as defined in the cut-off approach (Red: primary data; blue: generic data)

END-OF-LIFE APPROACH

Under this approach, the take-back and delamination of the PV modules are considered separately from the potential benefits gained by the recovered materials. The potential benefits are calculated by awarding credits for the avoided environmental impacts caused by the primary production of the replaced products (aluminium and silica sand[1]) and adding the impacts of secondary material production, see Fig. 2.2. This modelling approach can be used to illustrate the net environmental impacts of PV module delamination. A similar approach is required in the Product Environmental Footprint (PEF) pilot projects 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 delamination process.

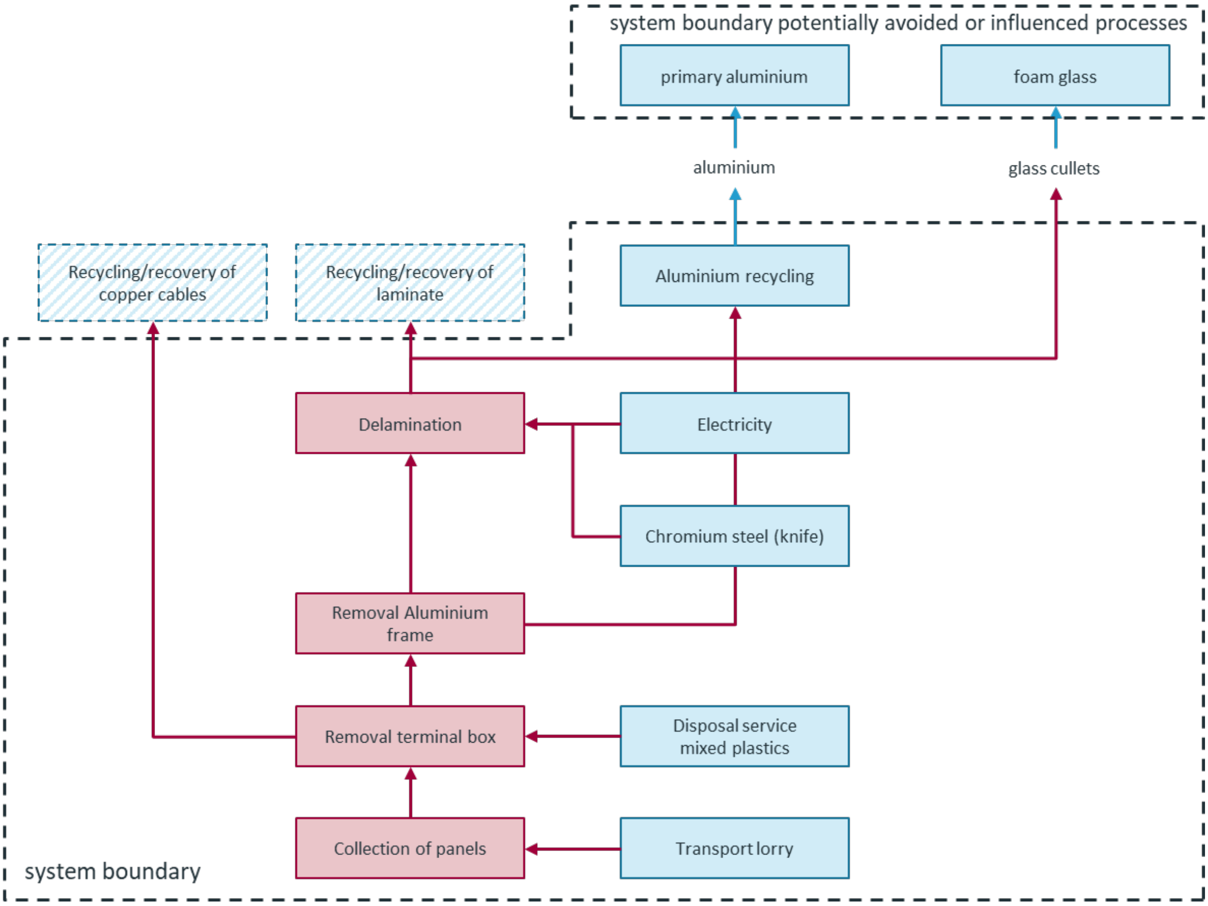

Fig. 2.2 System boundary and process outputs as defined in the EOL approach. (Red: primary data; blue: generic data; hashed box: not included in the assessment; "influenced": glass cullets replace silica sand and thus reduce the energy required to produce foam glass)

[1] Additionally, using glass cullets instead of silica sand in foam glass production reduces its energy consumption.

Note that the hot knife delamination technology delivers some components that need further treatment—namely, copper cables and the backsheet laminates (including the cells and ethylene vinyl acetate [EVA]). This external treatment is not part of the current LCA.

2.4 Data sources

A questionnaire was sent to the operator of the hot knife technology. The delamination company was asked to provide information on their energy and material consumption and the amount of the recovered materials. The disclosed information was used to establish an LCI of the hot knife delamination of c-Si PV panels. The LCI represents the delamination process in a pilot plant.

Tab. 2.1 Data sources used

Part of the product system	Data source	Data type
Hot knife delamination	NPC Inc. Ltd. 2021	Primary
Treatment of laminate (cell/EVA foil)	Not included in LCA	-
Treatment of copper cables	Not included in LCA	-
PV panel manufacturing and supply chains	PVPS Task 12 LCI data 2020	Secondary
Energy supply	UVEK LCA data DQRv2:2022	Secondary
Material supply	UVEK LCA data DQRv2:2022	Secondary
Transport services	UVEK LCA data DQRv2:2022	Secondary
Waste management services	UVEK LCA data DQRv2:2022	Secondary

For assessing the production and installation of the PV system, the data sets from the PVPS Task 12 LCI update 2020 (Frischknecht et al. 2020a) are used. For other processes, such as background processes for which no specific data were collected, the data sets in the UVEK LCA data DQRv2:2022 are used (KBOB et al. 2022).

2.5 Impact assessment indicators

The environmental impacts of the c-Si PV module delamination were quantified with selected impact category indicators of the International Life Cycle Data System (ILCD) Midpoint 2011 impact assessment method (European Commission et al. 2012), as recommended by the PVPS Task 12 LCA methodology guidelines (Frischknecht et al. 2020b). This study focuses on the following six impact categories:

- Particulate matter
- Freshwater ecotoxicity
- Human toxicity (noncancerous effects)
- Human toxicity (cancerous 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 Product Environmental Footprint Category Rules (PEFCR) (TS PEF Pilot PV 2019) as the most relevant for the generation of PV electricity. The selected impact category indicators also allow for comparisons of the environmental impacts of the delamination of PV modules to 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 HOT KNIFE TECHNOLOGY

3.1 Process description

The studied hot knife delamination process of c-Si PV modules (by NPC Incorporated) is an automated disassembly line consisting of a J-box separator, a frame separator, and a glass separator (hot knife technology), and it involves the following steps (see also Fig. 2.1 and Fig. 2.2):

- Removal of the terminal box (also known as the J-box), then the removal of the cables from the terminal box
- Removal of the aluminium frames
- Separation of the glass and EVA/cell/EVA/backsheet.

As shown in Fig. 3.1, the equipment for all these steps can be connected to achieve a fully automated disassembly line. After mechanically removing the terminal box, the aluminium frame removing equipment, shown in Fig. 3.2, automates the process of removing the aluminium frames. The equipment can be used with various shapes, structures, and sizes of frames while minimizing the mechanical stress on modules without crushing the glass; however, the model of the delamination unit analysed here cannot treat modules that have bent frames or broken glass.

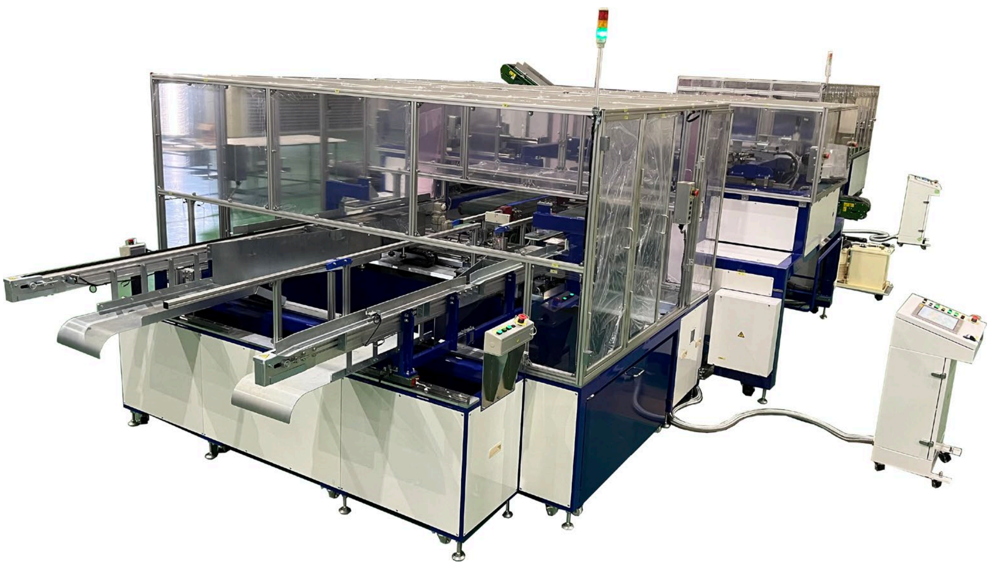

Fig. 3.1 Hot knife delamination equipment, including J-box separator, deframer, and delamination components (Photo courtesy of NPC Incorporated)

Fig. 3.2 Aluminium frame removing equipment (Photo courtesy of NPC Incorporated)

Fig. 3.3 shows the process of removing the aluminium frames. After a module is loaded into the equipment with a conveyor, it is pinched and fixed by the upper and lower fixing tables. Then the left and right chucks pull off the short frames, and the module rotation mechanism rotates the module 90 degrees on the table. Then the left and right chucks pull off the long frames, and the unloading conveyor unloads the module with all the frames removed.

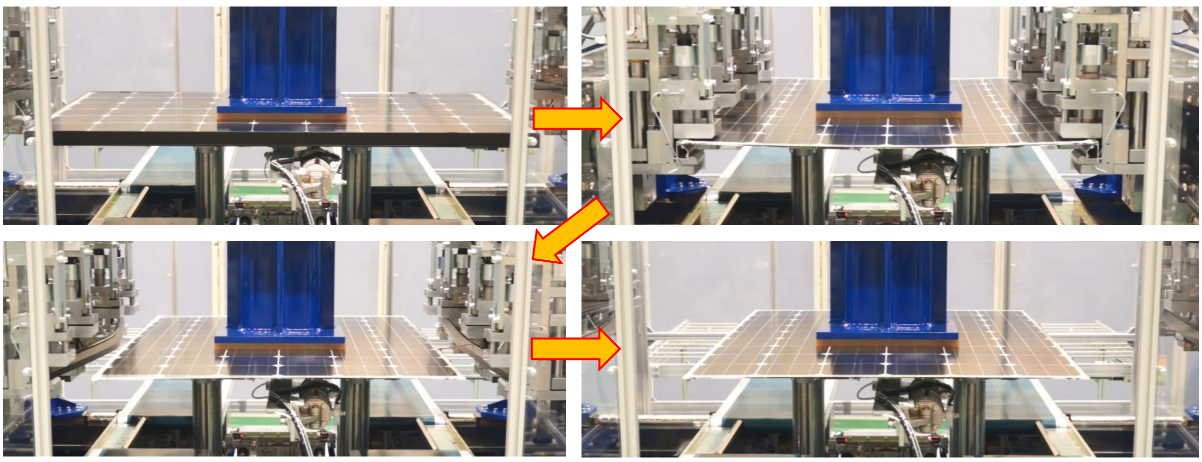

Fig. 3.3 Removal process of aluminium frames (Photo courtesy of NPC Incorporated)

In the next step, the glass and EVA separating equipment, shown in Fig. 3.4, successfully separates the glass from the EVA/cell layer with a heated cutter (i.e., a hot knife). The heated cutter adds heat to the EVA and separates it from the glass. There is no need to crush the glass, and the equipment collects the laminate, including the cells, the tabbing, the EVA layers, and the backsheet. The process takes approximately 50 seconds per module. After the process, the separated materials are unloaded onto a multistage conveyor, shown in Fig. 3.5.

Note that the pilot plant evaluated uses the hot knife technology, which requires flat, unbent modules as input. There is another version of this machine that can accept distorted or warped modules, but this technology was not evaluated in this study; however, we would expect results to be very similar to those reported here. Based on four years of experience, NPC Incorporated estimates that approximately 40% of decommissioned c-Si PV modules arrive at their delamination facility warped or distorted[2]; therefore, there is a significant need for PV recyclers that use the hot knife technology to evaluate which version of the technology is used in their facility or whether an alternative to delamination of warped or distorted modules is used.

Fig. 3.4 Module delamination, i.e., glass and EVA separating equipment (Photo courtesy of NPC Incorporated)

[2] It is possible that other recyclers might receive distorted modules at different proportions.

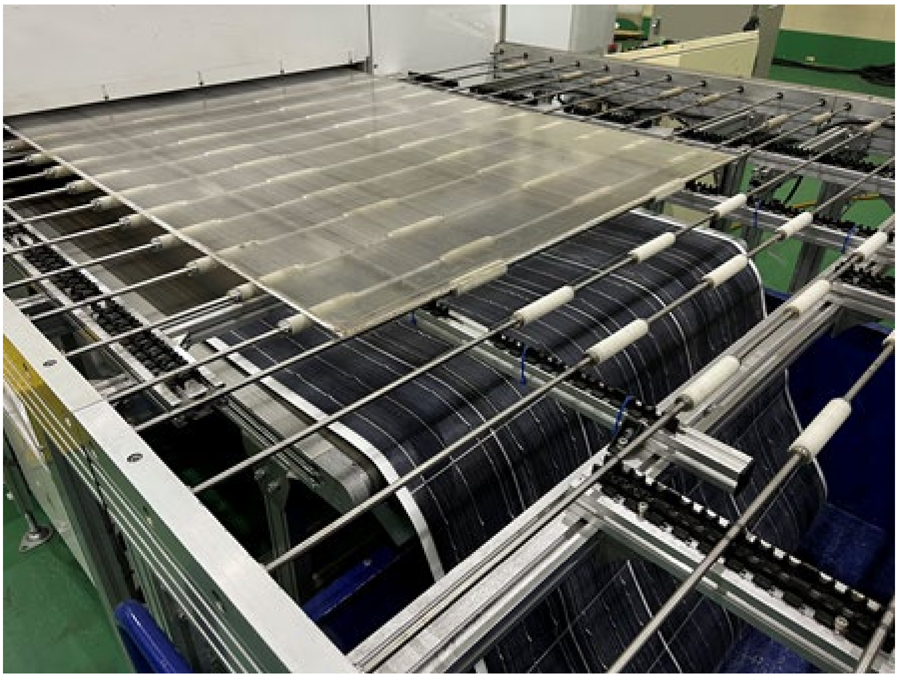

Fig. 3.5 Separated materials after the hot knife technology (Photo courtesy of NPC Incorporated)

Thus, the hot knife delamination process is a solution enabling automated separation of the frames and cell/EVA sheet from the glass without crushing the glass. The glass sheet can be sold to glass product manufacturers, and the cell/EVA sheet can be sent to refineries to extract metals such as copper and silver. The further treatment of the cell/EVA sheet and the copper cables is not part of the LCA documented in this report. The exclusion of the further treatment of the cells, the EVA, and the copper cables from our system boundary makes the LCA according to the EOL recycling approach incomplete.

3.2 Life cycle inventory data

The yield in different materials depends on the average bill of materials of the panels treated. This is one important reason for differences in yield. In the panels treated with the hot knife technology, approximately 70 % of the total mass of the panel is glass, followed by nearly 15 % aluminium, and 14 % laminates (see Tab. 3.1). Tab. 3.1 also shows the relative prices of the recovered materials and components and of the treatment service as well as the resulting derived allocation factors.

In particular, the copper used for solder and tabs is not recovered with the hot knife delamination, but it will be recovered together with silver at the external refinery company treating the laminate (cell/EVA sheet). Also, the copper cables are externally treated where the copper is recovered. Both downstream treatment processes are not included in this LCA.

Tab. 3.1 Mass fractions and relative prices of the treatment service and the materials and components recovered that are used to calculate the economic allocation factors for the cut-off modelling approach of the hot knife c-Si PV module delamination (Mass fraction data: NPC Inc. 2021; data on relative prices: personal communication, K. Komoto, April 2022)

hot knife c-Si PV module recycling	Mass fraction	Relative price (Japanese market)	Allocation factor
	kg/kg panel	-	-
Treatment service	1.000	1.000	**0.854**
Glass cullets	0.692	0.010	**0.006**
Aluminium scrap	0.146	1.000	**0.125**
Copper cables	0.009	1.400	**0.010**
Laminate: cell/EVA sheet	0.140	0.040	**0.005**

The data on the hot knife delamination of c-Si modules were compiled by Mr. Taisuke Doi, NPC Incorporated. The unit process data sets as displayed in Tab. 3.2 to Tab. 3.5 were established by Mr. Rolf Frischknecht.

Transport logistics were assumed conservatively, with 100 km lorry to a collection point and another 100 km with large lorries to the delamination facility.

Tab. 3.2 LCI unit process data of the take-back and delamination of 1 kg of c-Si panels with the hot knife technology; established based on data provided by NPC Inc. 2021

	Name	Location	InfrastructureProcess	Unit	takeback and recycling, hot knife, c-Si PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				JP			
	InfrastructureProcess				0			
	Unit				kg			
product	takeback and recycling, hot knife, c-Si PV module	JP	0	kg	1			
equipment	recycling, hot knife, c-Si PV module, machinery and buildings	JP	0	kg	1.00E+0	1	3.06	(2,3,1,1,3,4,BU:3); Data from recycling pilot plant;
energy	electricity, medium voltage, at grid	JP	0	kWh	3.50E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant;
consumables	chromium steel 18/8, at plant	RER	0	kg	8.10E-5	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant;
wastes	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	1.59E-2	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant;
transports	transport, freight, lorry 7.5-16 metric ton, fleet average	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, freight, lorry, fleet average	RER	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 100 km; Latunussa et al. 2016

Tab. 3.3 LCI unit process data of potentially avoided impacts of recovered materials using the hot knife technology from 1 kg of c-Si panels; established based on data provided by NPC Inc. 2021. This LCA is incomplete because the laminate (cell/EVA sheet) and copper cable need further treatment and thus would increase the amount of recovered materials.

	Name	Location	InfrastructureProcess	Unit	avoided burden from recycling, hot knife, c-Si PV module	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				JP			
	InfrastructureProcess				0			
	Unit				kg			
product	avoided burden from recycling, hot knife, c-Si PV module	JP	0	kg	1			
technosphere	natural gas, burned in industrial furnace 1MWth	CH	0	MJ	-8.51E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2022
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	-5.51E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2022
	silica sand, at plant	DE	0	kg	-3.60E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2022
	soda, powder, at plant	RER	0	kg	-1.43E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2016
	limestone, milled, packed, at plant	CH	0	kg	-2.49E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2022
	aluminium, primary, at plant	RER	0	kg	-6.44E-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-recommendation 2009/1:2022; Weighted average of data from recycling pilot plant; UVEK LCI data DQRv2:2022
	aluminium, secondary, from old scrap, at plant	RER	0	kg	6.44E-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	-1.29E-1	1	1.14	(2,4,1,1,3,BU:1.05); Avoided primary glass production materials; Weighted average of data from recycling pilot plant; Held and Ilg 2011; UVEK LCI data DQRv2:2022

Tab. 3.4 LCI unit process data of the hot knife technology equipment; established based on data provided by NPC Inc. 2021

	Name	Location	InfrastructureProcess	Unit	recycling, hot knife, c-Si PV module, machinery and buildings	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				JP			
	InfrastructureProcess				0			
	Unit				kg			
product	recycling, hot knife, c-Si PV module, machinery and buildings	JP	0	kg	1			
technosphere	Transformation, from unknown	-	-	m2	3.49E-5	1	2.07	(2,3,1,1,3,4,BU:2); Data from recycling pilot plant;
	Transformation, to industrial area	-	-	m2	3.49E-5	1	2.07	(2,3,1,1,3,4,BU:2); Data from recycling pilot plant;
	Occupation, industrial area	-	-	m2a	1.75E-3	1	1.58	(2,3,1,1,3,4,BU:1.5); Data from recycling pilot plant;
	building, hall	CH	1	m2	1.75E-5	1	3.06	(2,3,1,1,3,4,BU:3); Data from recycling pilot plant;
	metal working machine, unspecified, at plant	RER	1	kg	2.84E-4	1	3.06	(2,3,1,1,3,4,BU:3); Data from recycling pilot plant;
	synthetic rubber, at plant	RER	0	kg	2.38E-5	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant;

Tab. 3.5 LCI unit process data of treatment (delamination) of 1 kg of c-Si panels with the hot knife technology; allocation to treatment (delamination) and recovered materials and components according to the allocation factors shown in Tab. 3.1; established based on the data provided by NPC Inc. 2021. The copper cables and laminate (cell/EVA sheet) need further treatment to recover copper and silver, among other materials.

	Name	Location	InfrastructureProcess	Unit	treatment, hot knife, c-Si PV module	glass cullets, from c-Si PV module treatment, hot knife	aluminium scrap, from c-Si PV module treatment, hot knife	copper cables, from c-Si PV module treatment, hot knife	laminate, cell and EVA foil, from c-Si PV module treatment, hot knife	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				JP	JP	JP	JP	JP			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
product	treatment, hot knife, c-Si PV module	JP	0	kg	1	0	0	0	0			
	glass cullets, from c-Si PV module treatment, hot knife	JP	0	kg	0	1	0	0	0			
	aluminium scrap, from c-Si PV module treatment, hot knife	JP	0	kg	0	0	1	0	0			
	copper cables, from c-Si PV module treatment, hot knife	JP	0	kg	0	0	0	1	0			
	laminate, cell and EVA foil, from c-Si PV module treatment, hot knife	JP	0	kg	0	0	0	0	1			
equipment	recycling, hot knife, c-Si PV module, machinery and buildings	JP	0	kg	8.54E-01	8.54E-3	8.54E-1	1.20E+0	3.42E-2	1	3.06	(2,3,1,1,3,4,BU:3); Data from recycling pilot plant; Economic allocation;
energy	electricity, medium voltage, at grid	JP	0	kWh	2.99E-2	2.99E-4	2.99E-2	4.19E-2	1.20E-3	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant; Economic allocation;
consumables	chromium steel 18/8, at plant	RER	0	kg	6.92E-5	6.92E-7	6.92E-5	9.69E-5	2.77E-6	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant; Economic allocation;
wastes	disposal, plastics, mixture, 15.3% water, to sanitary landfill	CH	0	kg	1.36E-2	1.36E-4	1.36E-2	1.91E-2	5.45E-4	1	1.25	(2,3,1,1,3,4,BU:1.05); Data from recycling pilot plant; Economic allocation;
transports	transport, freight, lorry 7.5-16 metric ton, fleet average	RER	0	tkm	8.54E-2	8.54E-4	8.54E-2	1.20E-1	3.42E-3	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, freight, lorry, fleet average	RER	0	tkm	8.54E-2	8.54E-4	8.54E-2	1.20E-1	3.42E-3	1	2.09	(4,5,na,na,na,na,BU:2); Assumed transport distance to recycling site: 100 km; Economic allocation; Latunussa et al. 2016

4 LIFE CYCLE IMPACT ASSESSMENT

4.1 Overview

A comparison of the environmental impacts caused by the treatment of used PV modules with the hot knife technology and the production of the PV systems based on the LCIs according to the cut-off modelling approach is drawn in Subchapter 4.2. The LCIs according to the EOL modelling approach can be applied to estimate the net environmental impacts of PV module delamination with the hot knife technology (Subchapter 4.3). The methodology of the analyses is shortly introduced for both modelling approaches and is followed by a presentation and discussion of the results for c-Si PV modules.

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

The LCIs of PV module delamination according to the cut-off modelling approach complements the life cycle with data on the EOL treatment of PV systems. The relevance of the treatment of EOL 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 Frischknecht et al. (2020a). In this example, the PV system analysed encompasses the production of the PV modules, the mounting structure, the inverter, the electric installation, the transport of the components to the place of installation, and the installation itself. The environmental impacts during the use phase are neglected. The EOL treatment of the PV modules is modelled with the hot knife delamination technology described in previous sections.

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

The environmental impacts of the production of a c-Si PV system were calculated as the weighted average of multicrystalline and monocrystalline Si PV modules, determined as the share of the global installed capacity of each technology in 2018. As shown in Tab. 4.1, the hot knife treatment (delamination) of EOL 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 delamination efforts is observed for the climate change impacts (0.3 %). This is mainly caused by transport logistics and electricity consumption.

Note that the hot knife technology only delaminates the panel and does not recover copper and other metals on-site; it sends both the copper cables and the laminate (cell and EVA sheet) to an external recycling facility (refinery) where the plastic waste will be burned. The refinery pays for the cables and laminates and recovers copper and silver.

Tab. 4.1 Environmental impacts of the production and hot knife treatment (delamination) 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 LCI 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 Frischknecht et al. (2020a).

3 kWp c-Si PV system, mounted on a slanted roof, Recycling JP		Production	Treatment	Total	Treatment
		kg PV module			% of Total
Particulate matter	kg PM2.5 eq	1.96E-02	**2.09E-05**	1.96E-02	*0.1%*
Freshwater ecotoxicity	CTUe	5.40E+01	**8.11E-02**	5.41E+01	*0.1%*
Human toxicity, non-cancer effects	CTUh, n-c	5.04E-06	**9.41E-09**	5.05E-06	*0.2%*
Human toxicity, cancer effects	CTUh, c	3.63E-07	**7.15E-10**	3.64E-07	*0.2%*
Mineral, fossil & renew. resources	kg Sb eq	4.09E-03	**7.27E-07**	4.09E-03	*0.0%*
Climate change	kg CO2 eq	1.72E+01	**5.70E-02**	1.73E+01	*0.3%*

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

The net environmental benefits are calculated as the difference between the environmental impacts caused by the delamination of the PV modules and the potentially avoided burdens due to recovered materials from the delamination. It does not include further treatment and recovery processes (copper cables, laminates [cell/EVA foil]) and thus excludes potentially avoided environmental burdens due to the recovered materials in these further treatments. Negative numbers indicate that the delamination process yields net potential environmental benefits beyond the system boundary, implying that the environmental impacts of producing corresponding primary materials are higher than those caused by the PV delamination process. The results in the following sections are normalised to the environmental impacts of module delamination, which has net environmental impacts equal to 1.

The hot knife delamination of c-Si PV modules results in net environmental benefits according to all the indicators analysed (Tab. 4.2). High potential net environmental benefits result in human toxicity potential for cancer, particulate matter, as well as climate change (-53, -13, and -12). The potential benefits in the impact category for “mineral, fossil, and renewable resource depletion” are five times higher than those caused by the hot knife PV panel delamination.

Tab. 4.2 Net environmental impacts of hot knife delamination of c-Si PV modules according to the EOL modelling approach. Results are normalised to the impacts of module delamination (= 1; negative values: net potential benefits).

Impact category	c-Si PV module
Particulate matter	- 13.0
Freshwater ecotoxicity	- 6.2
Human toxicity, non-cancer effects	- 9.6
Human toxicity, cancer effects	- 53.0
Mineral, fossil & renew. resources	- 4.9
Climate change	- 12.0

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 aluminium have the highest impact in all indicators (Fig. 4.1, left).

The environmental impacts of c-Si PV panel delamination are mainly caused by the transport of the used panels to the delamination facility (200 km total) and by electricity supply (Fig. 4.1, right). Waste disposal is hardly visible in terms of impact. The contribution of transport varies with shipping distance.

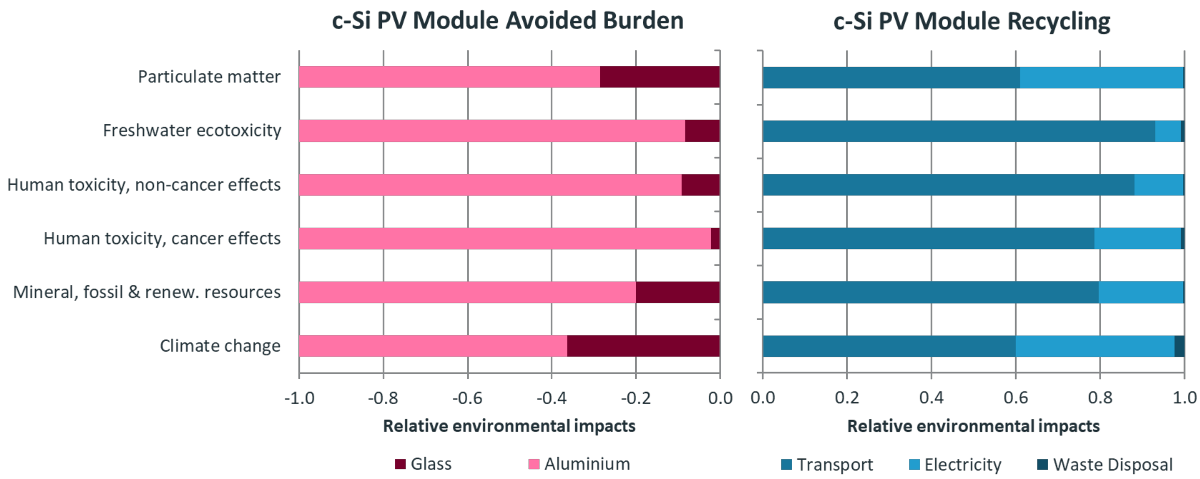

Fig. 4.1 Relative contributions of recovered glass and aluminium to the potential benefits *(left)* and relative contributions of the delamination processes to the environmental burdens *(right)* of the hot knife technology c-Si PV module delamination

5 DATA QUALITY, LIMITATIONS, AND UNCERTAINTY

The data quality of the LCIs of the hot knife technology for c-Si PV module delamination is classified by the authors as fair. The available data were obtained from a pilot plant operator in Japan. The treatment of a significant part of the PV panels—namely, the laminate (cell/EVA foil) and copper cables—and the recovery of copper and silver happens downstream of the hot knife delamination process in a refinery. These further treatment and recovery steps are outside the system boundary of this LCA. Although the LCA according to the cut-off approach is considered complete (both copper cables and laminate are sold, and thus they bear a share of the delamination efforts), the LCA according to the EOL approach is not complete (both further treatment efforts and potentially avoided impacts due to additional recovered materials are excluded). We recommend compiling data on copper cable and laminate treatment and the recycling of copper and silver to make the data of the LCIs more complete and robust.

The transport distance to the delamination facility was qualitatively estimated. An increase in the shipping distance by 100 % (400 km total) would increase the environmental impacts of PV panel delamination by between 60 % (greenhouse gas emissions, particulate matter) and 90 % (freshwater ecotoxicity). The environmental impacts of delamination relative to the impacts of manufacturing would increase to 0.5 % maximum.

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

6 CONCLUSIONS AND OUTLOOK

The environmental impacts caused by the hot knife technology of c-Si panel delamination are low compared to the environmental impacts caused by manufacturing the panels (including supply chain impacts). The specific environmental impacts attributed to the recovered materials are lower than the specific environmental impacts caused by sourcing the respective primary materials (aluminium, glass) from mines.

Data collection should be initiated on the treatment efforts and on the amount and qualities of the recovered materials by treating copper cables and laminates (cells/EVA foils). This is important for cases and countries where neither copper cables nor laminates (cells/EVA foils) can be sold but their treatment must be paid by the owner of the panels to be recycled.

The logistics of discarded panels strongly influences the environmental performance of the delamination process, as shown in the sensitivity analysis on transportation distance. Doubling transportation distance increases certain impacts by 60 %–90 %.

Further developments of the process might increase the amount and diversity of recovered materials—in particular, metals. Large-scale deployment of the process might also lead to lower efforts in energy and consumables per panel treated.

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