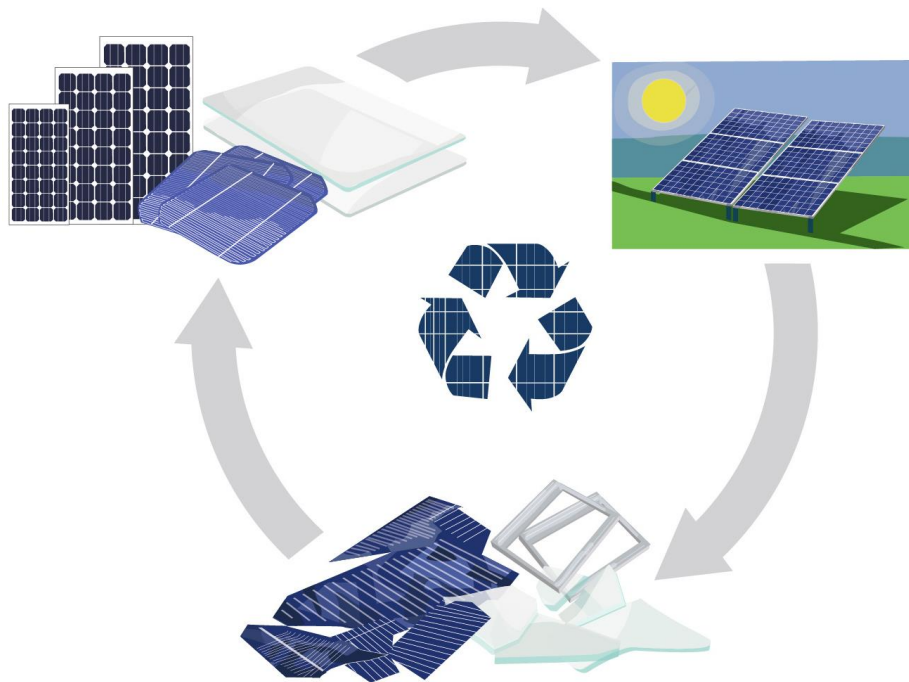


FINAL REPORT

END-OF-LIFE PATHWAYS FOR PHOTOVOLTAIC BACKSHEETS



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FINAL REPORT

END-OF-LIFE PATHWAYS FOR PHOTOVOLTAIC BACKSHEETS

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Oberhausen, 20 June 2017

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1 Executive Summary

The total amount of Photovoltaic (PV) waste generated globally amounted for about 45,000 tonnes in 2016, and is projected to increase to 1.7 million tonnes by 2030. Although this figure appears to be small in comparison to the global e-waste figure which stands around 45 million tonnes in 2016; the PV waste stream is rapidly evolving and is projected to reach 60 million tonnes by 2050. PV waste which falls under the e-waste category contains both valuable resources and hazardous substances. The recoverable valuable resources across various types of PV modules in general include aluminium, silver, copper, indium, gallium, tellurium, glass etc. The hazardous substances on the other hand are cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride etc. Therefore, the disposal or End-of-Life (EoL) processing of these substances in an environmentally friendly manner is vital to avert any contamination threats as well as improve resource efficiency.

From the legislation point of view, there is no specific entry in the European List of Wastes for the classification of the waste generated from the photovoltaic industry, but waste (e.g., derived from electric and electronic industrial equipment) containing halogenated compounds and/or heavy metals are classified as hazardous (Commission Decision 2000/532/EC; Directive 2008/98/EC; Directive 2012/19/EU; Directive 2000/76/EC). Furthermore, as the PV waste contains several hazardous materials as described above; these render them unsafe for open disposal. Legislatures around the world have now started to recognise PV waste as one of the immediate concerns that needs to be addressed. Although current EoL treatment methods such as incineration or landfilling can only provide an intermediary solution, they are however ineffective in handling the incoming surge of PV waste in the longer run. Typical incineration facilities of today can only handle homogenised waste streams with levels of contaminants stipulated by local emission standards. The European Union stands as the only political body that has until now developed targeted policies and regulations to address the end-of-life management of PV waste. The European WEEE Directive (Directive 2002/96/ EC) and the revised WEEE Directive of 2014 establishes legal framework for the collection and treatment of PV waste based on the principle of extended-producer-responsibility. Which now places the onus on the PV manufacturers for the collection, treatment and monitoring of PV waste. This Directive requires all producers supplying PV panels to the EU market (wherever they may be based

globally) to finance the costs of collecting and recycling of EoL PV panels that are sold to the European market.

Several scientific studies thus far have addressed the environmental impact of photovoltaics through life cycle assessments at various stages namely, manufacturing, operation & use and end-of-life. However, there has been no study thus far on the environmental impact of the fluoropolymers present in PV backsheet material. PV modules contain between 3 % and 10 % polymeric material by weight. Thus on an average, about 2,500 tonnes of polymeric backsheet material requires to be processed post the EoL stage per GW PV capacity installed. As of 2016, this amounts to about 800,000 tonnes of polymeric backsheet material that needs to be taken back and duly treated.

Fluoropolymers in PV modules are largely made of polyvinylidene fluoride (PVDF) or polyvinylfluoride (PVF) also known as Kynar® and Tedlar® respectively. The presence of these fluoropolymers makes it hard to thermally degrade or cost-effectively recycle the polymeric backsheet material present in PV modules. Furthermore, thermal degradation of fluoropolymers leads to toxic release of hydrogen fluorides with amounts beyond permissible regulations. Furthermore, the presence of fluoropolymers, halogenated-flame-retardants, etc. also increases the potential formation of dioxins during EoL treatment stage. Therefore, the option of typical landfilling also poses an equal risk if the fluoropolymer backsheet material leaches into the atmosphere and contaminate the soil and waterbodies.

Since the presence of fluorine or otherwise in the backsheet material could play a key part in determining the type and the economics of EoL treatment, this study undertook a comprehensive analysis to estimate and compare the environmental impact of fluorinated backsheet with fluorine-free backsheet. The scope of the project involved **experimental trials** to quantify the fluorine emissions resulting from the two EoL pathways namely incineration and pyrolysis; as well as **life cycle assessment (LCA)** for three EoL pathways namely incineration, pyrolysis and controlled landfilling.

For the experiments involving fluorine-free backsheet, PPE (PET-PET-EVA) samples were investigated. While KPK (Kynar®-PET-Kynar®) and TPT (Tedlar®-PET-Tedlar®) samples were investigated for Fluorinated backsheets. The experiments measured the emissions from the incineration and pyrolysis of all three backsheet materials at three different temperatures.

Furthermore, an LCA considering the ISO 14040/44 standards was conducted to analyse the potential environmental impacts namely abiotic depletion, acidification potential, eutrophication potential, global warming potential, ozone layer depletion potential, photochemical ozone potential and particulate

matter formation etc. for three EoL pathways - incineration, pyrolysis and controlled landfilling. The model assumptions for the backsheet material included – 100 % PET (modeling fluorine-free backsheet) and 100 % PVDF (modeling fluorinated backsheet). Although in reality a backsheet has several other material layers such as adhesives, EVA and primer. The model assumption was made to fully realise the respective environmental impacts of specifically the primary backsheet material in particular (i.e. PET and PVDF).

In conclusion, the key findings of this study are summarised as follows:

- The incineration experiments conducted at 750 °C, 850 °C and 950 °C show that the PPE backsheet samples did not have any halogenated compounds in its emissions as expected. Furthermore, it did not produce any noticeable residual ash. For KPK and TPT backsheets, a complete release of fluorine in the gas phase was measured already at 750 °C. The released fluorine amounts in the gas phase equalled to the actual fluorine content measured in the ultimate analysis which was conducted prior to incineration experiments.
- From the incineration experiments, it could be deduced that the incineration products will include toxic contaminants such as hydrogen fluoride (HF), fluoralkanes, contaminated particulate matter etc. Therefore, special care has to be taken in dedicated incineration facilities when incinerating PV backsheets containing PVF or PVDF after their EoL.
- The pyrolysis experiments were conducted at 300 °C, 400 °C and 500 °C. Where the PPE samples show a negligible mass loss at 300 °C, and up to 50 % mass loss at 500 °C, and 85 % mass loss at 500 °C. The remaining 15 % mass amounts to the residual char. The TPT samples were found to release most of its fluorine content already at 300 °C into the gas phase, but at 400 °C and 500 °C this share was even higher. In contrast to the high fluorine release at 300 °C, the mass loss observed was very low (10 %). The residual char from TPT after pyrolysis at 500 °C was 21 % and contained notable amounts of fluorine. Finally, KPK showed a different release behaviour of fluorine than TPT. At 300 °C no fluorine was released into the gas phase. At 400 °C, 66 % mass loss was observed and a release of large amounts of fluorine was subsequently noted. This release increased further at 500 °C. Similar to TPT and PPE not all volatiles were released at this temperature. Like TPT the char of KPK also contained notable amounts of fluorine.

- From the pyrolysis experiments, it could be inferred that the pyrolysis of fluoropolymers (such as TPT, KPK) is not a viable option as all the three pyrolysis products – pyrolysis gas, pyrolysis oil and pyrolysis char will be contaminated with hazardous halogenated compounds, and thus renders them unuseful for its intended traditional applications without expensive pre-and post-handling methods.
- The LCA for the fluorine-free backsheets show good results compared to the fluorinated backsheets for both incineration and pyrolysis.
- For Incineration, the LCA of fluorinated backsheets shows a more negative environment impact compared to the incineration of fluorine-free backsheets amongst all impact categories except for global warming potential (GWP). This could be attributed to the fact that PET molecule contains a higher amount of carbon than PVDF molecule and hence a higher impact on GWP.
- For pyrolysis, the LCA of fluorinated backsheets seems to be unfeasible both from an economic standpoint and the technical point-of-view in finding suitable pyrolysis product applications. Furthermore, treatment of the hydrogen fluoride present in the pyrolysis gas would demand large amounts of alkaline reagent and water, as well as a large effort for treating the effluent and in handling the resultant solid waste (chiefly Calcium fluoride). The pyrolysis oil and pyrolysis char fractions obtained in the products also contain high amounts of fluorine (in the form of halogenated hydrocarbons & aromatics), which renders their posterior application for energy recovery unsuitable due to toxicity hazards.
- In conclusion, the use of fluoropolymers or halogenated polymers in PV modules should be avoided and alternate PET based or biobased backsheets should be encouraged. If halogenated backsheets are used, they must be properly marked or labelled to inform both the users as well as the EoL managers. This labeling should comply with the ecolabelling standards and thus help the EoL managers in identifying and sorting the toxic fluoropolymer waste from other plastic waste during the EoL treatment of PV components.

2 Background

In light of the new European Union regulation (Directive 2012/19/EU-Recast) on Waste Electrical and Electronic Equipment (WEEE) and the Restriction of Hazardous Substances (RoHS), (Directive 2002/96/EC) mandating the manufacturers, retailers, and importers to collectively organise and finance the end-of-life stage of electronic products, this research aims to determine the environmental impact of processing the End-of-Life (EoL) stage of the backsheet material in PV modules.

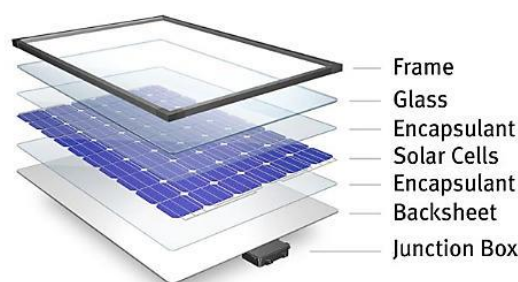
Investments as well as scientific research have been booming globally in the PV sector over the past decade. Europe in particular, accounted for about 50% or around 88 GW (IEA, 2014) of the worldwide installed capacity in 2014. This significant share could largely be attributed to the targeted EU policies aimed at achieving a renewable energy target share of 27% to be consumed in the EU by the year 2030 [Ardente et al., 2016]. Considering the sharp increase in photovoltaic infrastructure built across the world and the ever increasing installation capacities, it is estimated that the waste generated after the service-life of PV panels could amount to 20 million tonnes annually by the year 2050 [Mulvaney, 2015]. Therefore, the main environmental issues that could be linked to improper handling and disposal following the EoL of PV panels could be as follows: (a) leaching of toxic metals such as lead and cadmium, (b) loss of conventional resources such as glass, aluminium, (c) loss of critical metals such as silver, indium, gallium and germanium. [Monier, 2011].

An EoL process entails the take-back, collection, treatment, recovery and safe disposal of PV modules. Several scientific studies in the past have attempted to address this potential environmental impact through life cycle assessments [Held et al., 2011; Fthenakis et al., 2011; Giacchetta et al., 2013; Latunussa et al., 2016]. However, there has been no study thus far to the authors' knowledge on the environmental impact of the PV backsheet material. A PV backsheet as shown in Figure 2-1 is the outermost layer of the PV module, which acts as a protective layer to shield the inner components of the module, in specific the electrical components and the photovoltaic cell. Backsheet materials in general are polymeric layered materials that broadly fall into two categories – fluorinated and fluorine-free.

A typical crystalline PV module with aluminium frame and 60 cells has a capacity of 270 watt peak (Wp) and weighs 18.6 kilograms (kg) (e.g. Trina Solar TSM-DC05A.08). While a standard Cadmium-Telluride (CdTe) panel (e.g. First Solar FS-4100), with 110 Wp can be assumed to weigh 12 kg on average. Finally, a CIGS panel (e.g. Solar Frontier SF160-S) usually has a capacity of 160

Wp and weighs 20 kg [Weckend et al., 2016]. Across all these photovoltaic modules (c-Si, a-Si, CIGS and CdTe) the polymer composition including the photovoltaic backsheet can amount up to 10 % in panel weight. Thus on an average about 2,500 tonnes of polymeric backsheet material requires to be processed post the EoL stage per GW PV capacity installed. As of 2015, about 315 GW PV capacity has been installed globally [IEA-PVPS, 2016]. This consequently amounts to about 800,000 tonnes of polymeric backsheet material that needs to be avoided from ending in a landfill. Moreover, the use of fluoropolymers in backsheets also poses serious toxicity concerns when PV modules approach their EoL stage.

Figure 2-1:
A blowout illustration of PV module – with backsheet as the outermost protective layer. [Picture: DuPont]



Therefore this study serves as a scientific report drawn from experimental work, life cycle assessment as well as the established scientific literature to:

- I. Identify the relevant EoL pathways for both types of photovoltaic backsheets – Case (a) Fluorine containing backsheet, and Case (b) Fluorine-free containing backsheet.
- II. Estimate the emissions (to air) through fluorine release experiments experimental trials generated from pyrolysis and incineration for both the fluorinated and fluorine-free backsheet.
- III. Conduct Life Cycle Assessment (LCA) considering the ISO 14040/44 standards for analysing potential environmental impacts.

2.1 Scope of work

The scope of the project entails **experimental trials** to quantify the emissions resulting from the two EoL pathways, namely incineration and pyrolysis as well **environmental assessment** for all three EoL pathways namely incineration, pyrolysis and controlled landfilling.

The evaluation and assessment were performed based on backsheet samples provided by Coveme Spa and other backsheet samples available in the market. Experimental data generated through this study, scientific literature, as well as the modelling and calculations that was conducted using Life Cycle Assessment

(LCA) software (GaBi ts 7.3.3). The LCA methodology and results are shown in detail in chapter 5.

Experimental trials were done using Double Pipe Oven Analysis (DOPA) to measure the Fluorine content in the released gases emanating from the incineration and pyrolysis of the PV backsheet, as well as to quantify the fluorine in the residual char. Where, temperature and residence time were the key varying process parameters of this study. The experimental set-up and the findings are elaborate in chapter 4.

Within the overall scope of this work a comparative environmental assessment was conducted. The evaluation of possible environmental impacts namely global warming potential, acidification, eutrophication, particulate matter etc., was assessed and appropriate interpretation of findings are presented.

In summary, the scope of the work i.e., the EoL pathways for two backsheet cases that will be explored in this study are shown in Figure 2-2 and Figure 2-3.

Figure 2-2:
Case 1: PV backsheet
with fluorine

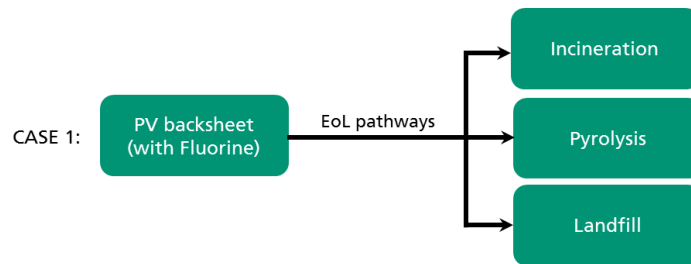
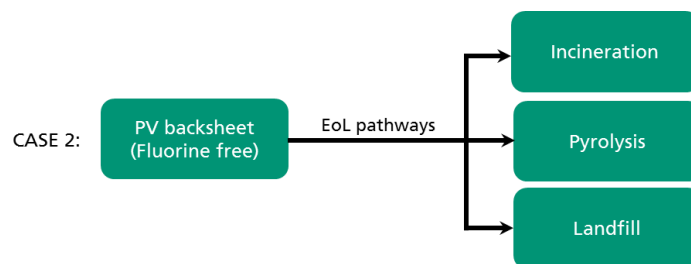


Figure 2-3:
Case 1: PV backsheet
without fluorine



2.2 Overall methodology

Experimental examinations

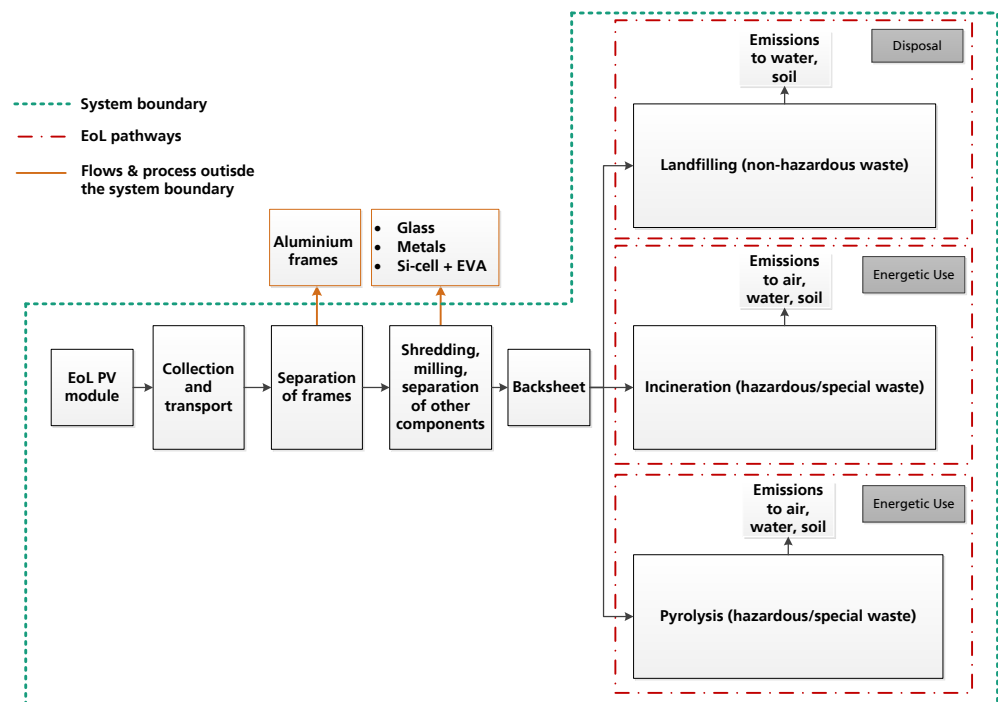
In general, ultimate and proximate analyses provide information on the overall composition of the particle substance after its incineration or pyrolysis. However, it is unknown whether this overall composition corresponds to the substance in the gas phase or in the residual char. It is also unknown whether the release behaviour is temperature controlled or kinetics controlled. In order to gain deeper knowledge as well as to detect the release behaviour of fluorine

(F), an experimental device to measure fluorine release dependent on temperature was set-up. The experiments were conducted at three different temperatures - 300 °C, 400 °C, 500 °C for pyrolysis experiments and 750 °C, 850 °C, 950 °C for incineration experiments. For both cases the post combustion of release gases was done at 1 000 °C. While flue gases and remaining char samples were then analysed to estimate the fluorine content resulting from the pyrolysis and incineration of backsheet.

Environmental assessment

A Life Cycle Assessment (LCA) considering the ISO 14040/44 standards was conducted to analyse the potential environmental impacts namely global warming potential, acidification, eutrophication, particulate matter, etc. for the EoL pathways of PV waste. The system boundaries of the LCA are illustrated in Figure 2-4.

Figure 2-4:
PV Waste EoL process
flow sheet



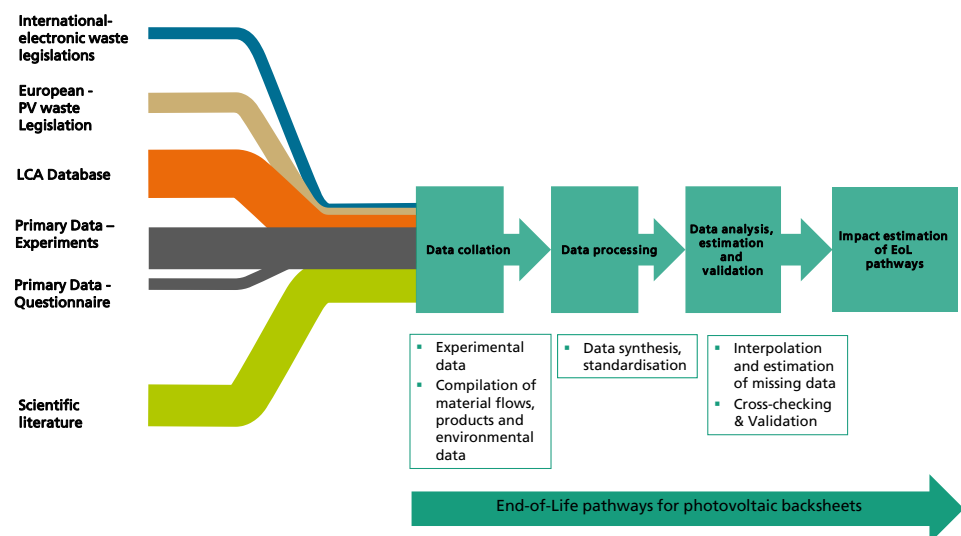
The functional unit considered for this assessment was 1 000 m² PV backsheet material. The analysis conducted follows an “End-of-Life” approach considering all the relevant impacts extending from the delivery of the PV waste to the recycling plant, sorting and de-manufacture products into material components, and the final processing of the backsheet. The system boundaries for this study, as shown in Figure 2-4, accounts for all energy (thermal and electricity), auxiliary material consumptions, as well as emissions along each stage. It estimates the impacts due to pyrolysis, incineration as well landfill. The

LCA does not consider the further treatment of PV components such as metals and glass fractions apart from the intended PV backsheets. The energy generated from incineration and pyrolysis products was modelled as co-products and suitable credits were given for the avoided environmental impacts that would otherwise be a burden if this energy were to be produced by conventional means.

The LCA relies on the experimental data generated in this study, a spectrum of secondary data from scientific literature, as well as the inventory data provided by the GaBi ts and Ecoinvent databases. The Life Cycle Impact Assessment (LCIA) was modelled in GaBi ts 7.3.3 applying the CML characterisation factors developed by the Leiden University [Guinée et al., 2002]. The range of environmental impacts as revealed earlier was estimated, interpreted, documented and reported. All data sets were evaluated for their suitability, consistency and implications on the overall study.

Figure 2-5 outlines the research methodology and the spectrum of primary and secondary data used in conducting this study.

Figure 2-5:
Research Methodology



3 The Photovoltaic industry

3.1 Evolution of the photovoltaic technology

First Generation

Traditional solar cells are made from silicon and account for around 90 percent of all the solar panels sold around the world. In general silicon based solar cells are more efficient and last longer than non-silicon based cells. However, they are more at risk to efficiency loss at higher temperatures than thin-film solar cells which are made from thin wafers of silicon (monocrystalline solar cells). Furthermore, growing large crystals of pure silicon is a difficult and energy-intensive process; the cells are characterized by high production costs and efficiencies in the range of 10 - 20%. [Lewis et al., 2005]

Panels based on polycrystalline silicon are cheaper per unit area than monocrystalline panels, but they are also slightly less efficient (up to 19.3%). String ribbon is a method for producing multi-crystalline silicon strips suitable for the photovoltaic industry. Ribbon silicon is a material with a multi-crystalline structure. Where, flat thin films are drawn from molten silicon to form ribbon silicon. Ribbon silicon cells have less conversion efficiency, but they can be produced without sawing from ingots, making them more cost effective. Typically a cut wafer will convert 15-16% of the incoming light into electricity where string ribbon solar cells are capable of converting 13-14%. This technology has reached an efficiency of about 18.3% in laboratory tests; however it cannot be produced commercially yet. [Nakayashiki et al., 2006]

Second Generation

Second-generation solar cells are known as thin-film solar cells (layers of semiconductor materials are only a few micrometres thick). Because of less material and lower manufacturing cost, this technology is produced and sold at a much lower price. There are three types of solar cells: amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). The later two types are made from non-silicon materials. However, many of these cells are not yet marketable, so their market share is still low.

Third Generation

Finally, in the third generation there are more solar cells with complicated techniques, whose efficiency is far higher than the previously achieved values., This new generation of solar cells is made from variety of new materials besides silicon, including nanotubes, silicon wires, and solar inks using conventional

printing press technologies, organic dyes, and conductive plastics. Currently, most of the work on third generation solar cells is being done in the laboratory and is simultaneously being commercialised by new ventures. [Ginley et al., 2008]. Figure 3-1 below shows the distribution of the percentage of global annual production of various generations of photovoltaics (in GWp) by technology. Where the Si-wafer based PV technology still accounts for the majority of the total production (about 93 %) in 2015, with a production capacity of 59 GWp globally. For the same year, the market share of thin film technologies amounted to about 8 % of the total annual production with a production capacity of 4.2 GWp globally. [Fraunhofer ISE, 2016]

Figure 3-1:
PV Production capacity
-Development by
Technology [Fraunhofer
ISE, 2016]

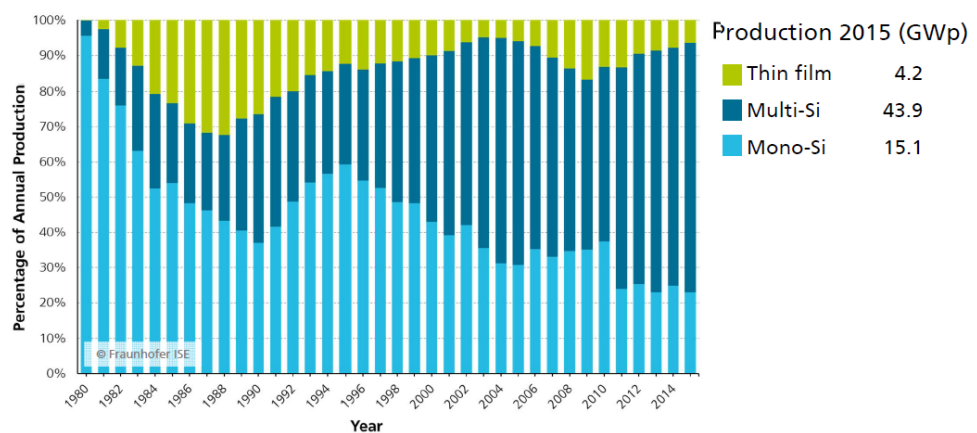


Table 3-1 below shows the market share of PV panels by technology groups.

Table 3-1: Market share of PV panels by technology groups [Weckend et al., 2016]

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92,0%	73,3%	44,8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2,0%	5,2%	6,4%
	Cadmium telluride (CdTe)	5,0%	5,2%	4,7%
Other	Concentrating solar PV (CPV)	1,0%	1,2%	0,6%
	Organic PV/dye-sensitised cells (OPV)		5,8%	8,7%
	Crystalline silicon (advanced c-Si)		8,7%	25,6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0,6%	9,3%

3.2 Production volumes – Global & EU

The International Energy Agency Photovoltaic Power Systems Programme (IEA - PVPS) countries represented more than 156 GW of cumulative PV installations altogether, mostly grid-connected, at the end of 2014 (See Table 3-2 below).

Table 3-2: Worldwide installed photovoltaic capacity in GW [Volker-Quaschnig, 2017]

Country	2013	2014	2015
China	19,72	30,38	43,53
Germany	35,77	38,25	39,71
Japan	13,60	23,34	34,15
USA	12,08	18,32	25,60
Italy	18,07	18,61	18,91
United Kingdom	3,38	5,65	9,50
France	4,73	5,70	6,59
Spain	4,64	5,38	5,43
Australia	3,23	4,09	5,11
Republic of Korea	1,48	2,48	3,49
Belgium	3,01	3,15	3,25
Canada	1,21	1,90	2,58
Netherlands	0,72	1,12	1,56
Thailand	0,82	1,30	1,42
Switzerland	0,76	1,06	1,39
Austria	0,63	0,79	0,94
Israel	0,48	0,68	0,89
Denmark	0,56	0,61	0,79
Portugal	0,28	0,42	0,47
Turkey	0,02	0,06	0,27
Malaysia	0,07	0,20	0,23
Mexico	0,11	0,11	0,17
Sweden	0,04	0,08	0,13
Norway	0,01	0,01	0,02
Other	14,38	13,31	21,62
Total World	139,8	177,0	227,7

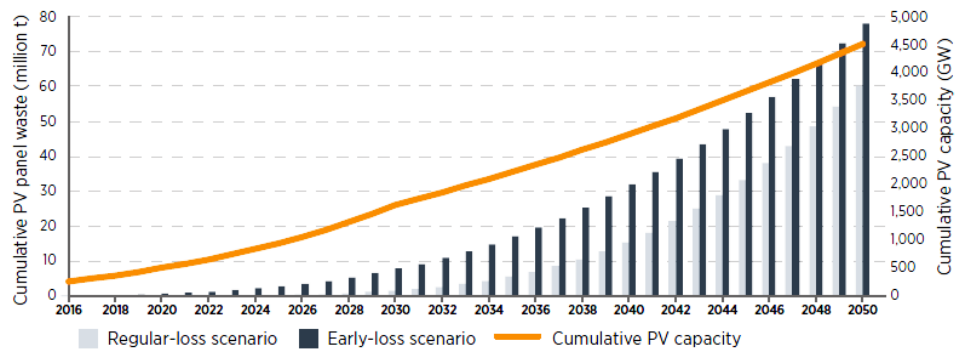
The other 38 countries that have been considered and are not part of the IEA PVPS Programme represented 21 additional GW, mostly in Europe: UK with close to 5,6 GW, Greece with 2,6 GW, Czech Republic with 2,1 GW installed, Romania with 1,2 GW and Bulgaria with 1,0 GW and below the GW mark Ukraine and Slovakia. Outside of Europe, the major countries that accounted for the highest cumulative installations in 2014 were India with more than 3 GW, South Africa with 0,9 GW, Taiwan with 0,6 GW and in Chile with 0,4

GW. Some sources have recently verified PV shipments in countries outside of the traditional PV markets and concluded that at the end of 2014 an additional 1,6 GW of PV systems have been installed in the last years [IEA-PVPS, 2015]. Presently it appears that 227 GW represents the minimum installed capacity by end of 2015 with a firm level of certainty.

3.3 Estimated waste volumes – Global & EU

The IRENA-Study [Weckend et al., 2016] is the first to quantify PV panel waste at a global scale and across different PV technologies. In summary, this study develops two scenarios – regular-loss and early-loss – to account for the above uncertainties about the mechanisms and predicted timing of panel failures.

Figure 3-2:
Estimated cumulative global waste volumes (million t) of end-of-life PV panels [Weckend et al., 2016]



In the regular-loss scenario, the PV panel waste accounts for 43,500 tonnes by the end 2016 with an increase projected to 1.7 million tonnes in 2030. An even more drastic rise to approximately 60 million tonnes could be expected by 2050. The early-loss scenario projection estimates much higher total PV waste streams, with 250,000 tonnes alone by the end of 2016. This estimate would rise to 8 million tonnes in 2030 and total 78 million tonnes in 2050. This is because the early-loss scenario assumes a higher percentage of early PV panel failure than the regular-loss scenario. [IEA-PVPS, 2015].

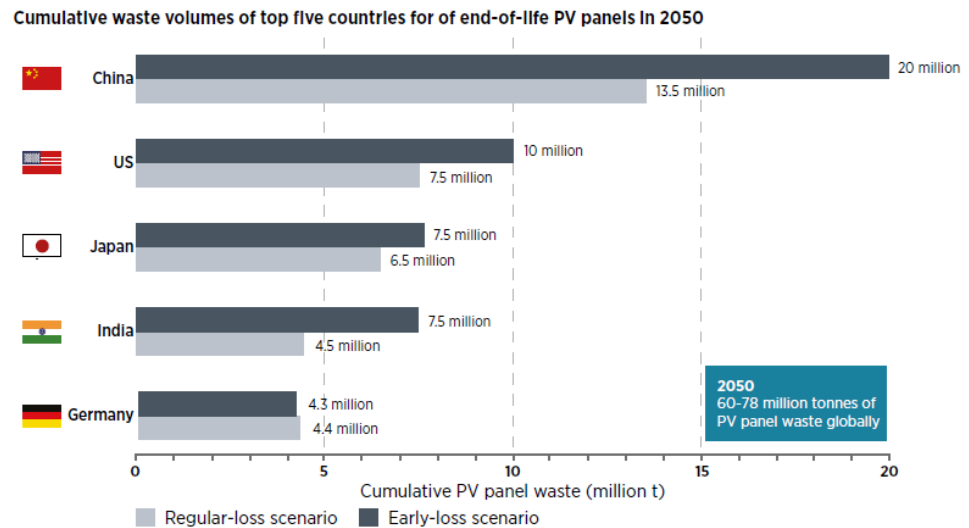
Table 3-3: Modelled results of estimated cumulative waste volumes of end-of-life PV panels by country (in tonnes) [IRENA-IEAPVPS]

Year	2020		2030		2040		2050	
	regular loss	early loss	regular loss	early loss	regular loss	early loss	regular loss	early loss
Asia								
China	8,000	100,000	200,000	1,500,000	2,800,000	7,000,000	13,500,000	19,900,000
Japan	15,000	100,000	200,000	1,000,000	1,800,000	3,500,000	6,500,000	7,600,000
India	2,000	15,000	50,000	325,000	620,000	2,300,000	4,400,000	7,500,000
Republic of Korea	1,500	10,000	25,000	150,000	300,000	820,000	1,500,000	2,300,000
Indonesia	45	100	5,000	15,000	30,000	325,000	600,000	1,700,000
Malaysia	100	650	2,000	15,000	30,000	100,000	190,000	300,000
Europe								
Germany	20,000	200,000	400,000	1,000,000	2,200,000	2,600,000	4,300,000	4,300,000
Italy	5,000	80,000	140,000	500,000	1,000,000	1,200,000	2,100,000	2,200,000
France	1,500	25,000	45,000	200,000	400,000	800,000	1,500,000	1,800,000
United Kingdom	650	15,000	30,000	200,000	350,000	600,000	1,000,000	1,500,000
Turkey	100	350	1,500	11,000	20,000	100,000	200,000	400,000
Ukraine	150	2,500	5,000	25,000	50,000	100,000	210,000	300,000
Denmark	100	2,000	4,000	22,000	40,000	70,000	130,000	125,000
Russian Federation	100	350	1,000	12,000	20,000	70,000	150,000	200,000
North America								
United States of America	13,000	85,000	170,000	1,000,000	1,700,000	4,000,000	7,500,000	10,000,000
Mexico	850	1,500	6,500	30,000	55,000	340,000	630,000	1,500,000
Canada	700	7,000	13,000	80,000	150,000	300,000	650,000	800,000
Middle East								
United Arab Emirates	50	100	3,000	9,000	20,000	205,000	350,000	1,000,000
Saudi Arabia	300	1,000	3,500	40,000	70,000	220,000	450,000	600,000
Africa								
South Africa	450	3,500	8,500	80,000	150,000	400,000	750,000	1,000,000
Nigeria	250	650	2,500	30,000	50,000	200,000	400,000	550,000
Morocco	10	100	600	2,000	4,000	32,000	50,000	165,000
Oceania								
Australia	2,000	17,000	30,000	145,000	300,000	450,000	900,000	950,000
Latin America and Caribbean								
Brazil	40	100	2,500	8,500	18,000	160,000	300,000	750,000
Chile	250	1,500	4,000	40,000	70,000	200,000	400,000	500,000
Ecuador	15	100	250	3,000	5,000	13,000	25,000	35,000
Total	100,000	850,000	1,700,000	8,000,000	15,000,000	32,000,000	60,000,000	78,000,000

As of today, the PV waste volumes amount to only 0.5 % of the global e-waste, but these figures are expected to rise to over 10% of 2014 global e-waste levels by the year 2020 [IEA-PVPS Report: June 2016]. Figure 3 3: shows

the cumulative waste volumes for top 5 countries according to the two scenarios.

Figure 3-3: Cumulative waste volumes (million t) of top five countries for end-of-life PV panels in 2050 [Weckend et al., 2016]



3.4 Recoverable resources in photovoltaic modules

The various components of major PV panel technologies will influence material and waste characterisation as well as the economics of EoL treatment pathways. c-Si technology consists of slices of solar-grade silicon, also known as wafers, made into cells and then assembled into panels and electrically connected. The standard cell consists of a p-doped wafer with a highly doped pn-junction. The surface is usually textured and may show pyramid structures (monocrystalline silicon) or random structures (polycrystalline silicon) and an anti-reflective layer to minimise the reflection of light. To form an electric field, the front and back of the cell are contacted using grid-pattern printed silver and aluminium pastes.

The different technology types typically differ in terms of materials used in their manufacturing and can contain varying levels of hazardous substances that must be considered during handling and processing.

PV R&D has specifically set priority topics for material use reduction or substitution for different components commonly used in current PV panels including for:

- c-Si panels: glass, polymer, silicon, aluminium, silver, lead and others;
- CIGS panels: glass, polymer, aluminium, cadmium, gallium, indium, selenium and others;
- CdTe panels: glass, polymer, cadmium telluride, nickel and others.

Table 3-4: Composition of c-Si- and thin-film - modules [Bine Informationsdienst, 2010]

PV module components	c-Si (crystalline silicon cell)	a-Si (amorphous silicon cell)	CIS (copper-indium-diselenide cells)	CdTe (cadmium-telluride cells)
Percentages in %				
Glass	74	90	85	95
Aluminium	10	10	12	< 0,01
Silicon	ca. 3	< 0,1		
Polymers	ca. 6,5	10	6	3,5
Zinc	0,12	< 0,1	0,12	0,01
Lead	< 0,1	< 0,1	< 0,1	< 0,01
Copper (cable)	0,6		0,85	1,0
Indium			0,02	
Selenium			0,03	
Telluride				0,07
Cadmium				0,07
Silver	< 0,006			< 0,01

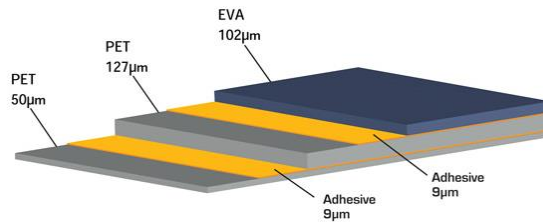
3.5 Role of backsheet in photovoltaic module

Backsheets are one of the critical components' used in the assembly of a PV module. The PV backsheet being the outermost layer protects both the inner structural components such as the PV cells, electrical circuitry, as well as acts as a support base for the entire module. Some of the key function so the PV backsheet includes:

- Protection from humidity and being hydrolysis resistant
- Providing colour stability
- Providing electrical insulation
- Providing UV protection for a 10 % albedo

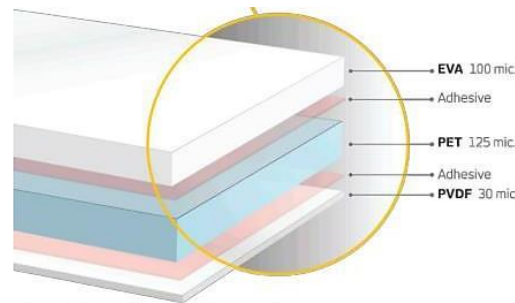
Backsheets are made up of consecutive layers of polymer films and adhesives and in general there are four common types of PV backsheets. (1) Fluorine-free backsheets; (2) Kynar® based backsheets; (3) Tedlar® based backsheets and (4) Fluoropolymer coated backsheets. Fluorine-free backsheets in general are PPE (PET-PET-EVA) backsheets, where the backsheet construction consists of PET (polyester) and EVA (ethyl vinylacetate) as shown in Figure 3-4.

Figure 3-4:
PPE backsheet [graphic:
Adhesives and Sealants
Industry, 2012]



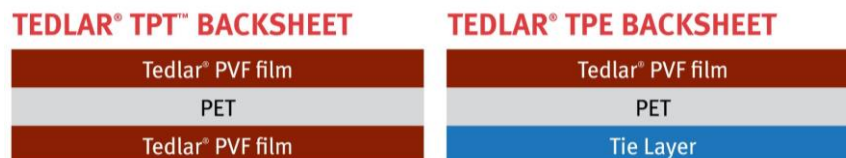
Kynar® based backsheets (see Figure 3-5) either has the configuration of KPE or KPK. While KPE is made of Kynar®-PET-EVA and KPK is made of Kynar®-PET-Kynar®. Here Kynar® is an industrial name for fluoropolymer resin based coatings developed by Arkema. The fluoropolymer used is Polyvinylidene fluoride (PVDF).

Figure 3-5:
KPE backsheet [graphic:
Hanita Coatings, 2017]



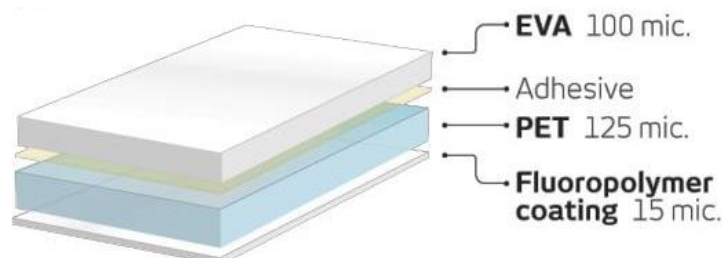
Tedlar® based backsheets (as shown in Figure 3-6) consists of TPT (Tedlar®-PET-Tedlar®) or TPE (Tedlar®-PET-EVA). Tedlar® is an industrial name for fluoropolymer material developed by Dupont, where the fluoropolymer is Polyvinyl fluoride (PVF).

Figure 3-6:
TPT, TPE backsheet
[graphic: DuPont,
2017]



Finally, the fluoropolymer coated backsheets as depicted in Figure 3-7 contains a layer of fluoropolymer coating in addition to the Pet and EVA layer.

Figure 3-7:
CPE backsheet
[graphic: Hanita
Coatings, 2017]



It should be noted that all backsheet types except for fluorine-free PPE backsheet contains fluoropolymers which pose both environmental and economic concerns during recycling or EoL stage processing.

4 End-of-Life treatment - Experiments

4.1 Experimental set-up and methodology

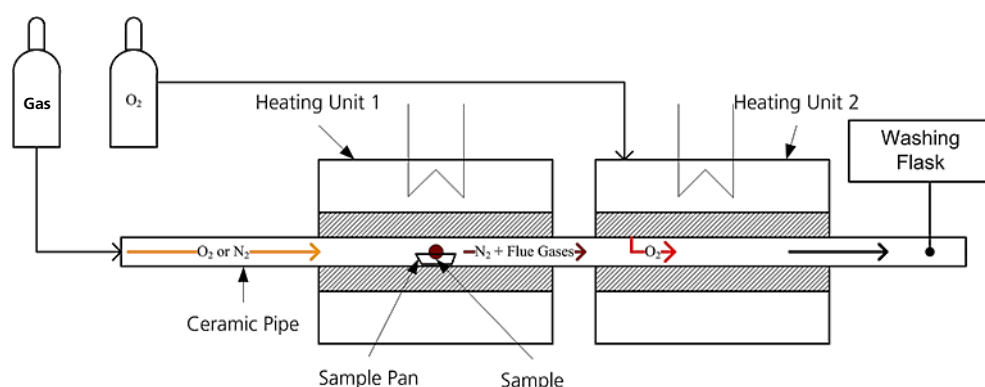
To measure fluorine release during the thermal decomposition of PV backsheets, it is necessary to set up a two-stage oven system with two heating units. These heating units surround a pipe with gas flowing through it. This gas is technical air (21 % O₂, 79 % N₂) for incineration experiments or an inert gas (100 % N₂) for pyrolysis experiments. The pipe can be made of ceramic or quartz glass. Preliminary experiments with reference materials (see chapter 4.2) have shown that quartz glass is suitable and the released fluorine reacts with the system walls.

The experimental set-up as shown in Figure 4-1 was designed with the following features:

- sample insertion is made via a pan, sample size 1 cm² (10 mm x 10 mm)
- operating temperature can extend from 20 °C to 1000 °C and
- prompt heating (units are heated to target temperature before the sample is inserted)
- wash flasks for flue gases to measure fluorine content using ion chromatography

In this system, single particles have been incinerated and pyrolysed. The two ovens used in this experimental set-up are electrical heaters, which are independently controlled with a heating range up to 1000 °C. The Pipe diameter was 23 mm, while its length was 1 m.

Figure 4-1:
Experimental set-up for
temperature related
Fluor release analysis



The flue gas released from the stage one of the thermal decomposition process (incineration or pyrolysis) is post-combusted in the second zone and then directed into washing flasks. Where, fluorine is diluted and can be readily

analysed using a ion chromatography (IC).The picture above shows a sketch of the setup which was operated under a safety hood considering the toxicity of released fluorine and its compounds.

Experimental design

The aim of the study was to identify whether fluorine-based PV backsheet systems will exhibit a fluorine release into the flue gas during thermal decomposition, and to subsequently compare these results with results from fluorine-free backsheets. For this reason release experiments have been carried out with three backsheet materials, where pyrolysis and incineration was investigated and analysed at three varying temperatures. The three backsheet materials are as follows:

- PPE (PET/PET/EVA)
- KPK (Kynar®/PET/ Kynar®)
- TPT (Tedlar®/PET/ Tedlar®)

Prior to the fluorine release experiments, reference experiments with reference materials was conducted to ensure high measurement quality and to quantify experimental or measurement errors. All experiments with backsheet materials have been conducted thrice to overcome any uncertainties. The final Carbon residues (resultant char) have also been analysed with respect to the fluorine content.

The expected results are therefore a brief comparison of the fluorine release behaviour of the PV backsheets for all three backsheet cases shown in Table 4-1. These results should also show temperature dependency of fluorine release and whether there is a contrast between pyrolysis and incineration.

Prior to the experiments, all backsheet samples have been analysed to estimate fixed carbon, ash (EN 15403) and volatiles content (EN 15402). The results are shown in Table 4-1. Sample KPK was found to have the highest fixed carbon content and lowest ash content. PPE contains the most volatiles and the ash content is nearly similar to the TPT sample.

Table 4-1: Proximate analysis of samples

Type of backsheet	Fixed carbon (wt% db)	Volatiles (wt% db)	Ash content (wt% db)
PPE	2,9	92,2	4,9
TPT	8,2	86,1	5,7
KPK	10,7	88,2	1,1

The backsheet samples have also been analysed to estimate elemental composition (according to EN 15407, EN 15408) and lower heating value (according to EN 15400). These results are shown in Table 4-2.

In addition, calorimetric measurement as described in EN 15408 was done by incinerating the sample inside a bomb calorimeter (similar to Cl- and S-measurements). The absorption solution from the bomb was then analysed via IC (EN ISO 10304) to measure fluorine content.

The sample PPE as expected does not contain any fluorine. While the highest fluorine concentration was found in the KPK sample.

Table 4-2: Ultimate analysis and heating value of samples

Type of Plastic	C	H	O	N	F ¹	Heating value
	(wt% db)					(kJ/kg db)
PPE	63,8	6,6	24,5	0,2	0,0	30,0
TPT	55,6	4,5	28,5	0,2	5,5	26,6
KPK	54,9	4,3	30,5	0,2	9,0	24,6

¹: measured via calorimeter

All analyses have been conducted on dry weight basis (db).

4.2 Reference experiments

As reference materials pure PVDF and a PVDF-Cellulose mixture were analysed via incineration with the experimental set-up. The reference experiments have been conducted to test the set-up system concerning the recovery rate of fluorine. All results are shown in the table below.

Table 4-3: Reference materials, results

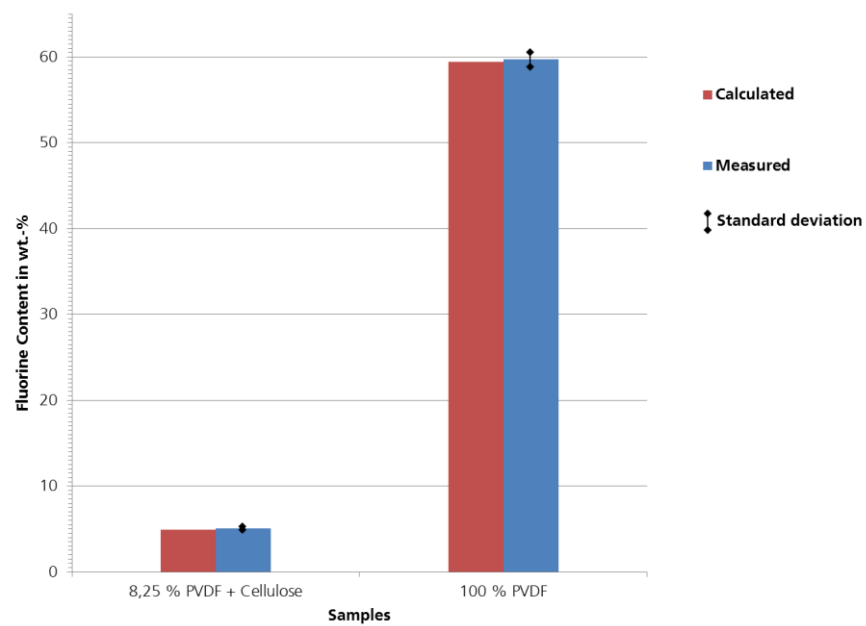
Reference-Material	Theoretical fluorine-content in wt.-%	Measured fluorine-content in wt.-%	Avg. measured fluorine-content in wt.-%	Relative deviation theory/measured in %
PVDF	59,4	61,5	59,7	0,5 %
		57,8		
PVDF-cellulose mixture	4,9	5,0	5,1	4,1 %
		5,1		
		5,2		

(wt.-% = weight-%)

Results in Table 4-3 show little differences between theoretical content and actual measured values. It can also be observed that the system can cope with very high concentrations up to 60 wt.-% fluorine, but is also sensitive to low concentrations around 5 wt.-%.

Therefore it can be concluded that the measurement method described in chapter 4.1 is suitable for conducting the investigation. However, relative deviations up to 5 % have to be considered. Figure 4-2 below shows a graphical version of the reference experiment results and highlights a very good fluorine recovery rate.

Figure 4-2:
Reference
measurements



4.3 Incineration experiments

4.3.1 Experiment description

The incineration experiments have been conducted at three different temperatures. Each test was conducted thrice and average values were calculated. Table 4-4 below shows the schemata of the incineration experiments, comprising of 27 experiments in total.

Table 4-4: Experimental Schemata

Sample	Temperatures in °C	Repetition
PPE	750, 850, 950	3
TPT	750, 850, 950	3
KPK	750, 850, 950	3

4.3.2 Incineration results

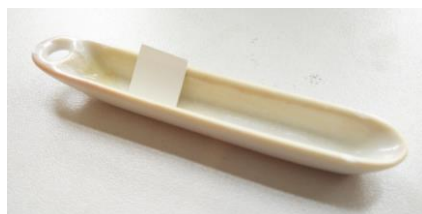
Table 4-5 shows the results and the boundary conditions of the incineration experiments. The samples were provided by COVEME Europe (Figure 4-3).

Figure 4-3:
Samples, provided by
COVEME Europe



All samples have been cut out from different areas across the backsheet to obtain representativeness. The areas have been chosen randomly. The sample size was 1 cm² and due to varying densities, sample masses shown below (Table 4-5) differ slightly. A sample pan containing 1 cm² of test material is shown in Figure 4-4.

Figure 4-4:
Sample pan with
backsheet before
experiment



As expected the PPE sample did not release fluorine at any given temperature, which also concurs with the results in Table 4-2. TPT and KPK samples on the other hand released all fluorine even at the chosen lowest incineration temperatures of 750 °C. Where all released fluorine could be detected in the gas phase.

Table 4-5: Incineration results

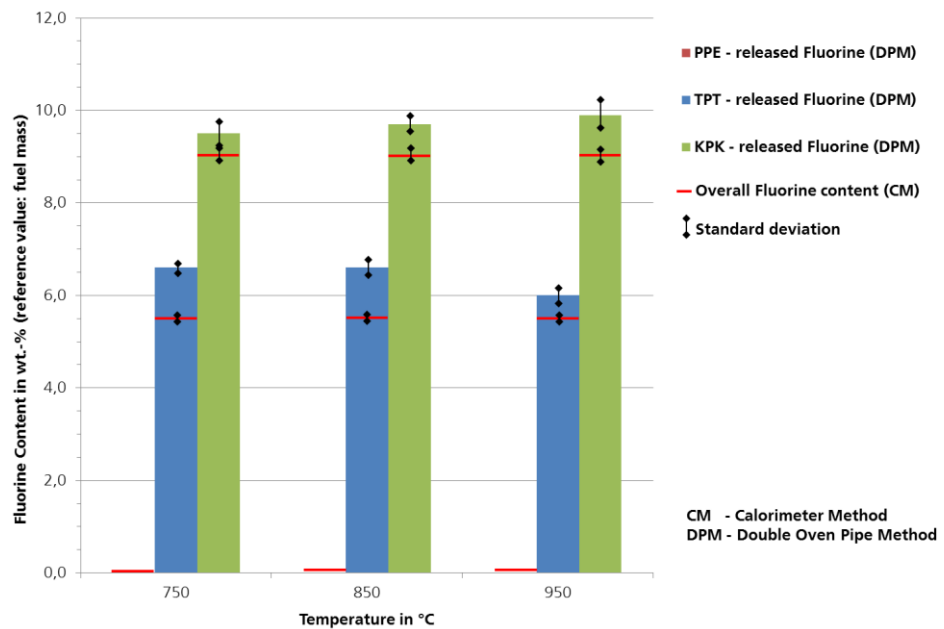
Sample	Sample size in cm ²	Initial mass in mg	Temperature in °C	Final mass in wt.-% ²	Gas fluorine-content in wt.-% ¹
PPE	1	30,7	750	4,9	0,0
	1	32,8	850		0,0
	1	31,8	950		0,0
TPT	1	46,1	750	5,7	6,6
	1	59,1	850		6,6
	1	48,2	950		6,0

Sample	Sample size in cm ²	Initial mass in mg	Temperature in °C	Final mass in wt.-% ²	Gas fluorine-content in wt.-% ¹
KPK	1	54,1	750	1,1	9,5
	1	52,9	850		9,7
	1	43,0	950		9,9

1: wt.-% referring to sample mass
2: Taken from proximate analysis

Figure 4-5 shows a graphical version of the experimental incineration results. It can be noted that all the fluorine is released into the gas phase, even at the lowest incineration temperature of 750 °C.

Figure 4-5:
Incineration
measurements



In summary, the incineration results show a complete release of fluorine into the gas phase for both TPT and KPK. As expected no fluorine is released from PPE. It was observed that the amount of fluorine released does not depend on the chosen incineration temperatures. These released fluorine values were higher than the values shown in the Table 4-2, which is explained by different measurement methods (see chapter 4.1).

As Figure 4-3 shows, the double oven pipe system measures more fluorine than the calorimetric method (CM). Due to different measurement methods there is an observable deviation.

4.4 Pyrolysis experiments

4.4.1 Experiment description

Similar to the incineration experiments, the pyrolysis experiments were also conducted at three different temperatures. Each test was conducted thrice and average values were calculated. Table 4-6 below shows the schemata of the pyrolysis experiments which comprised of 27 pyrolysis experiments. This includes 27 incineration experiments (for the resultant char in the pyrolysis). This yields to 54 measurements in total.

Table 4-6: Experimental Schemata

Sample	Temperatures in °C	Repetition
PPE	300, 400, 500	3
TPT	300, 400, 500	3
KPK	300, 400, 500	3

4.4.2 Pyrolysis results

Table 4-7 shows the results and boundary conditions of the pyrolysis experiments. All samples have again been cut out from different areas from the respective backsheet to obtain representativeness. Sample size was 1 cm² and due to different and due to varying densities, sample masses shown below differ slightly. Sample preparation was done in the same way as for incineration experiments.

Again, as expected, PPE sample did not release fluorine at any temperatures, which also concurs to the results in Table 4-2. At 300 °C mass loss was negligible. At 400 °C pyrolysis caused up to 50 % mass loss and at 500 °C 85 % mass loss was detected. In comparison to Table 4-1, the results show that even at 500 °C not all volatiles (92 wt.-%) have been released.

TPT releases most of its fluorine content at 300 °C into the gas phase, but at 400 and 500 °C this share is even higher. It can however be noted that, not all the fluorine content is released into the gas phase, even at 500 °C. Some amounts still remain in the residual char. In contrast to the high fluorine release at 300 °C, the mass loss is very low. Therefore, it can be concluded that the gas phase concentration of fluorine at 300 °C will be very high.

In reference to Table 4-1 it can be deduced that not all volatiles (86 wt.-%) are released at 500 °C. This is confirmed in Table 4-2, which shows that some

amount of fluorine still remains in the residual char. These values were confirmed by residual char analysis (see Table 4-7, last column).

Table 4-7: Pyrolysis results

Sample	Sample size in cm ²	Initial mass in mg	Temperature in °C	Final mass in mg	Final mass in wt.-%	Gas fluorine-content in wt.-% ¹	Residue fluorine-content in wt.-% ¹
PPE	1	36,4	300	36,2	99,4	0,0	0,0
	1	44,9	400	21,7	48,0	0,0	0,0
	1	43,7	500	6,2	14,3	0,0	0,0
TPT	1	69,8	300	63,7	91,3	4,8	0,7
	1	70,1	400	24,4	34,8	5,6	0,2
	1	66,2	500	14,0	21,0	5,5	0,1
KPK	1	74,6	300	74,2	99,4	0,0	9,3
	1	84,5	400	28,5	33,7	7,7	1,0
	1	63,2	500	14,5	22,9	8,3	0,7

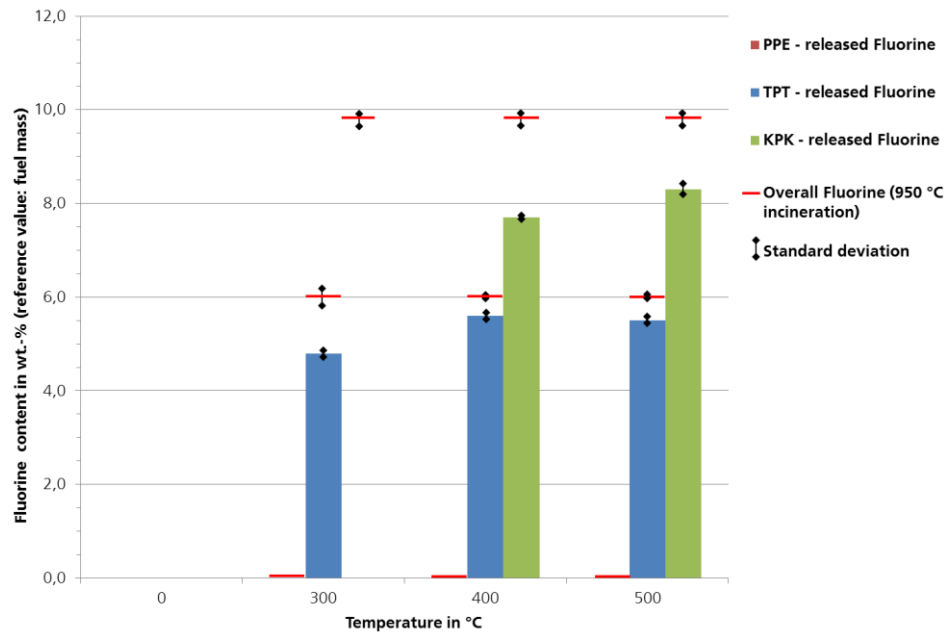
¹: wt.-% referring to sample mass

KPK shows different release behaviour of fluorine than TPT. At 300 °C no fluorine was released into the gas phase. At 400 °C a 66 % mass loss was observed and a sudden release of large amounts of fluorine can be noted. This release increases further at 500 °C. Similar to TPT and PPE not all volatiles are released at this temperature. Like TPT the char of KPK still contains a small share of fluorine in the residual char.

Figure 4-6 comprises of the results from Table 4-7 on the fluorine release into the gas phase. It can be observed that fluorine release of KPK starts at higher temperatures than of TPT. It can also be observed that, not all the fluorine content is released into the gas phase for pyrolysis of TPT and KPK backsheets.

The overall fluorine content (red bars) for the comparison in this picture was measured in the pipe oven system by incinerating the sample at 950 °C. It can be concluded that fluorine still remains in the char, even after high pyrolysis temperatures of 500 °C. Results of this conclusion are shown in chapter 4.4.4.

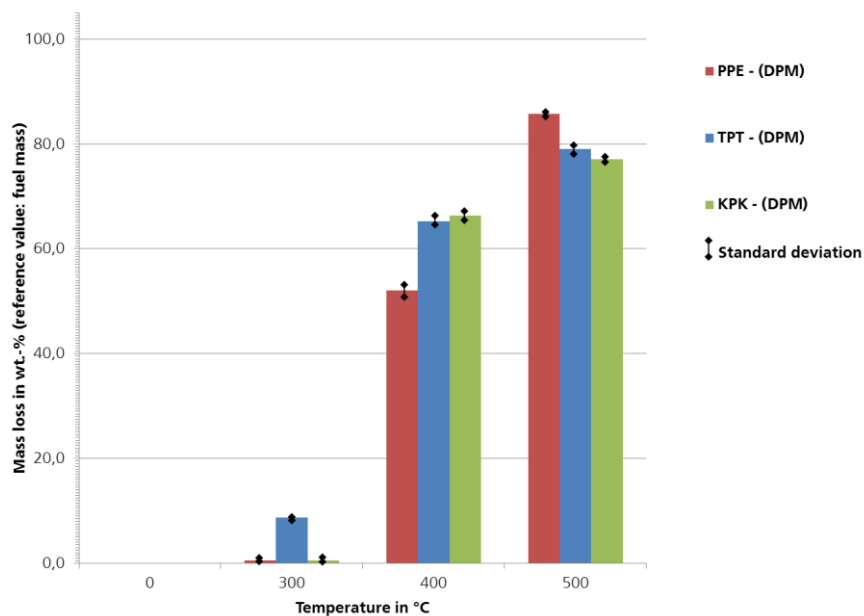
Figure 4-6:
Pyrolysis measurements



4.4.3 Effect of increase in temperature on sample mass loss

Figure 4-7 shows the mass loss of PPE, TPT and KPK caused at different pyrolysis temperatures and is drawn from the values given in Table 4-7. For the TPT backsheet, mass loss starts already at 300 °C, whereas for PPE and KPK the fluorine release and mass loss can be detected at 400 °C. Mass loss of all three samples increases at 500 °C but still do not reach amount of volatile content that was measured in Table 4-1.

Figure 4-7:
Pyrolysis
measurements, mass
loss



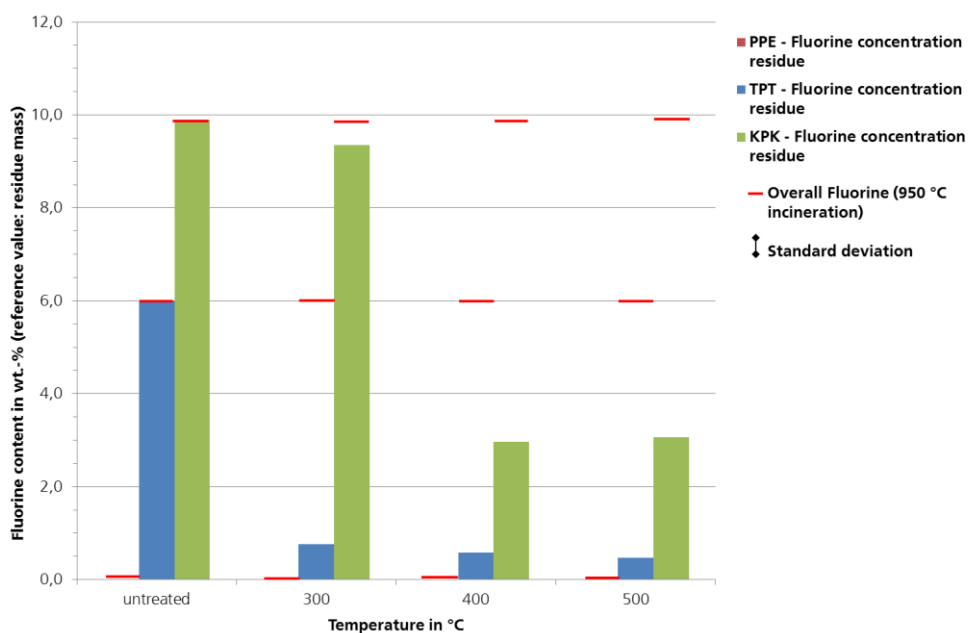
4.4.4 Material balances

Finally, following pyrolysis, the remaining char residues (see Figure 4-8) were incinerated to measure the fluorine content left in the solid phase. Figure 4-9 shows the results. The results show that the char from the pyrolysis of TPT still contains some fluorine, but most of it is removed due to devolatilisation, already at 300 °C. For KPK, a high concentration of about 9 wt.-% fluorine is released at 300 °C pyrolysis, which drops to around 3 wt.-% at higher temperatures but does not drop any further.

Figure 4-8:
Pictures of char residues (from left to right PPE, TPT, KPK; top down 300 °C, 400 °C, 500 °C)

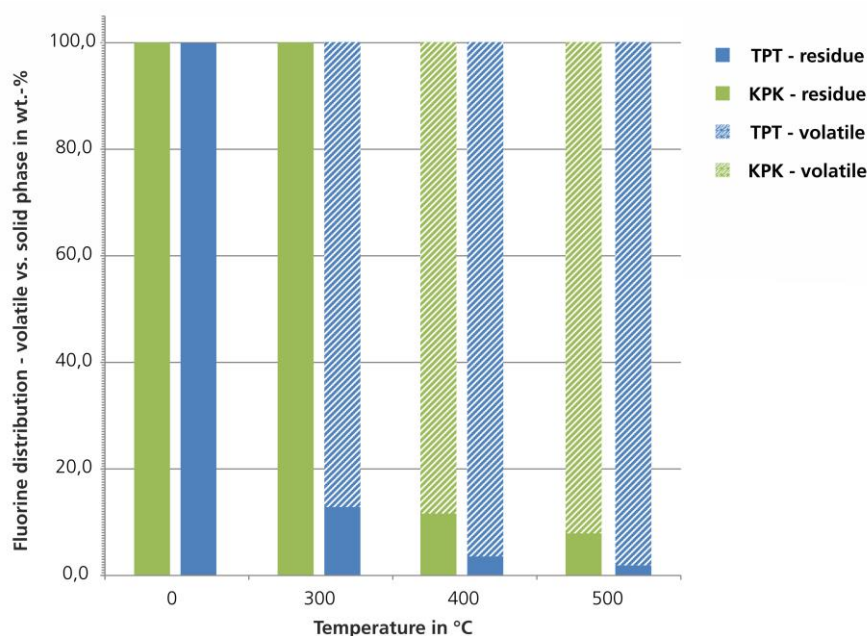


Figure 4-9:
Pyrolysis measurements, char analysis



Experimental results from Table 4-7 can be used to calculate fluorine distribution between the gas phase and the residual char. Figure 4-10 below compares in detail the fluorine distribution in the volatile phase and the solid phase for TPT and KPK backsheets. PPE is excluded from this analysis due to the absence of fluorine in the backsheet material. In conclusion, it can be observed that a large amount of fluorine is released primarily in the gas phase and only a smaller share remains in the residual char. The backsheets - TPT and KPK behave differently, where the fluorine release from TPT starts at 300 °C and fluorine release from KPK only starts at 400 °C.

Figure 4-10:
Pyrolysis
measurements, fluorine
distribution



4.4.5 Interpretations

Pyrolysis experiments have been conducted at three different temperatures (300 °C, 400 °C, 500 °C), and for each temperature a three-fold repetition was done. As expected PPE did not release any fluorine (refer Figure 4-6).

At 300 °C KPK did not release fluorine, but TPT on the other hand already shows a release. Same observations can be made in the mass loss (see Figure 4-7). It can therefore be propounded that for KPK the devolatilisation starts only at temperatures above 300 °C in comparison with TPT.

At 400 °C however, all the three materials show a significant mass loss. TPT and KPK release a large part of their fluorine content into the gas phase. At 500 °C KPK releases even more, whereas fluorine release from TPT remains the same.

Figure 4-10 shows the distribution of fluorine to gas and solid phase for different pyrolysis treatment temperatures. In contrast to the incineration experiments not all the fluorine present is transferred into the gas phase. Analysis of the residual char showed significant amounts of fluorine (Figure 4-9) in the solid phase for TPT and KPK. This char therefore is clearly not suitable for energy utilisation because of the high amounts of the fluorine present in it.

5 End-of-Life treatment - Life Cycle Assessment

The life cycle assessment for this study comprises a definition of the goal and scope (section 5.1), a life cycle inventory analysis (section 0), an impact assessment and an interpretation of the results (section 5.2.4) according to the ISO 14040:2006 standard (DIN EN ISO14040).

5.1 Goal and scope

The goal, scope and functional unit are specified in section 5.1.1, the systems under study and their boundaries are described in section 5.1.2; other methodological assumptions are explained in section 5.1.3, and the selected life cycle impact assessment methods are considered in section 5.1.4.

5.1.1 Goal, scope and functional unit

The main goal of this LCA study is to compare three chosen EoL management options for the backsheets contained in a typical crystalline silicon (c-Si) PV module: The EoL management pathways are - (1) incineration, (2) pyrolysis, and (3) controlled landfilling. Two different backsheet materials were considered: (1) Fluorine free, backsheet containing only PET as the main polymer, and (2) fluorinated, containing only PVDF as the main polymer. Although PV backsheet films are not composed of single polymers (PET or PVDF alone) (see section 3.5), it was assumed that the individual assessment of these specific polymers would point out the main environmental aspects associated with the management of the primary material in the fluorine-free backsheets and fluorinated backsheets respectively. Table 5-1 indicates the classification of the considered scenarios.

Table 5-1: EoL scenarios considered in the LCA study

Scenario	No.	Description
Landfilling	1.1	Landfilling fluorine-free backsheet (PET)
	1.2	Landfilling fluorinated backsheet (PVDF)
Incineration	2.1	Incineration fluorine-free backsheet (PET)
	2.2	Incineration fluorinated backsheet (PVDF)
Pyrolysis	3.1	Pyrolysis fluorine-free backsheet (PET)
	3.2	Pyrolysis fluorinated backsheet (PVDF)

The selected functional unit is the end-of-life management of 1 000 m² of backsheet material separated from a photovoltaic module. The geographical scope is Europe. Landfilling and incineration processes reflect current treatment

options (Dams, Hintzer 2017; Olson et al. 2015). On the other hand, pyrolysis technologies thus far are not yet in a fully commercial scale. There are only three industrial plants in Europe that use pyrolysis to treat solid waste (e.g., municipal solid waste, industrial waste, plastic waste) (Chen et al. 2015). The pyrolysis technologies employed aims at converting certain waste fractions (e.g., waste plastics) into recyclable products or high quality fuels by thermal decomposition (typically between 400 °C and 600 °C) in the absence of oxygen (Jung, Fontana 2006). Pyrolysis of fluoropolymers however, is still currently being investigated as an option for the recycling with some initial success with polytetrafluoroethylene (PTFE) (Dams, Hintzer 2017).

The LCA study follows an attributional, “end-of-life” approach. It considers the environmental impacts derived from: (1) the collection and transport of the PV waste to a treatment plant, (2) initial treatment operations, (3) energy recovery (depending on the scenario), and (4) disposal of the waste generated during the energy recovery processes. This study only includes the operational stage of the treatment facilities and equipment but not the construction or the deconstruction stages. It does not include either the impacts associated with the final treatment of the PV module fractions other than the backsheet material that are in general obtained after the initial treatment of the entire PV module.

5.1.2 Systems under study

In this section, the systems (scenarios) under study are described in detail. In each of these scenarios, the end-of-life management of a PV module starts with the collection and transfer of the module to a pre-treatment plant. Although different recycling processes for crystalline Si modules are being studied (BINE Informationsdienst 2010; Weckend et al. 2016; Latunussa et al. 2016), common initial steps for the treatment for c-Si PV waste by means of commercially available technologies in Europe include: (1) separation of the aluminium frame and junction box, which is usually carried out manually; and (2) shredding, milling and separation of fragments into recyclable material components, such as glass cullet, impure glass and copper foil, from non-recyclable yet recoverable fractions: e.g., fragments of c-Si wafers still embedded with ethylene vinyl acetate (EVA), and fragmented backsheet with other impurities (Alsema, Wild-Scholten 2007; Goris et al. 2015; Held 2013; Olson et al. 2015).

Subsequently, the waste fraction containing fragmented backsheet is landfilled, incinerated or pyrolysed according to each respective scenario. As indicated in section 5.1.1, fluorine-free backsheet waste was considered to be entirely composed of PET, while fluorinated backsheet waste was considered to be made of PVDF.

Landfilling of backsheet material

Before transferring the backsheet waste to a controlled landfill, it is treated as described in section 5.1.2 in a pre-treatment plant that is 200 km away from the collection site. After separation from the PV module, each type of backsheet material (PET or PVDF) is disposed of in a controlled landfill for non-hazardous waste (Plastics Europe 2012) which is about 200 km from the treatment plant. There is a lack of information on other possible pollutant emissions released from organic polymers deposited in landfills; e.g., of antimony leached from PET (Snedeker 2014) or fluoride leached from fluoropolymers. Therefore, in this study it was assumed that both types of backsheet waste (fluorinated and fluorine free) are disposed of in a closed landfill for plastic waste.

Incineration of backsheet material

Incineration (and pyrolysis) of hazardous waste, whose management is assigned to the industrial producers needs to be carried out in hazardous waste incineration plants (European Commission 2006). Non-hazardous waste can be incinerated in a mixed municipal solid waste incinerator that accepts industrial waste in smaller amounts, or alternatively, can be separately incinerated in a dedicated, industrial or commercial scale non-hazardous waste incineration plant (European Commission 2006).

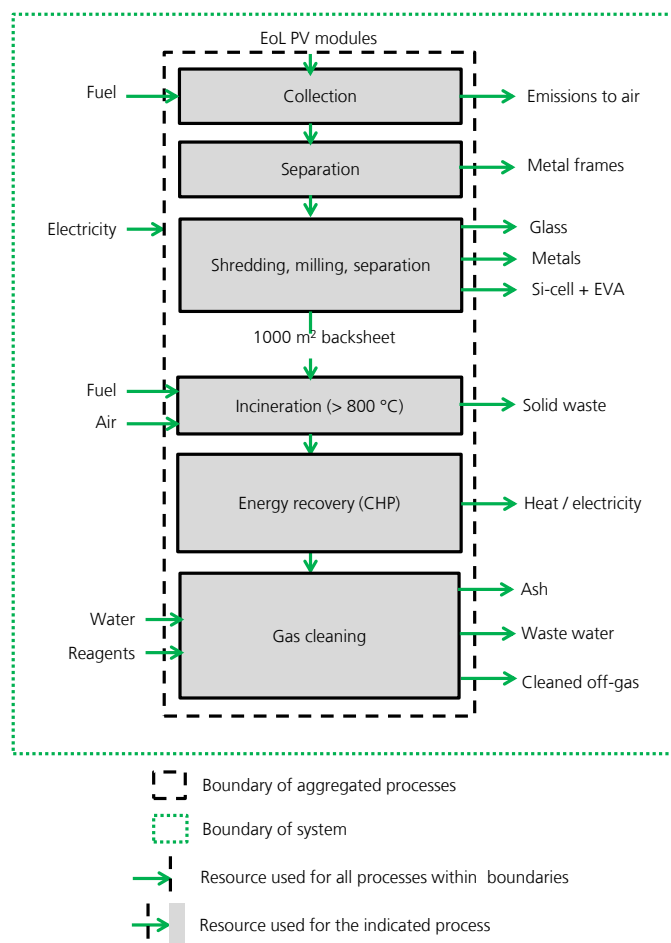
PET was considered to be incinerated in a dedicated, non-hazardous waste incineration plant (scenario 2.1), since PET is not classified as hazardous waste. Incineration of PVDF on the other hand (scenario 2.2) was assumed to be carried out in a hazardous waste incineration plant. A distance of 400 km was assumed for the collection and transport processes included in scenario 2.1, while a distance of 600 km was assumed for the collection and transport processes modelled in scenario 2.1. Since the incineration plants for hazardous waste are sparser than incineration plants for non-hazardous waste the average transport distance was assumed to be higher.

As shown in Figure 5-1, the main processes considered for incineration in both scenarios (scenarios 2.1 and 2.2) are similar. Firstly, the waste is mixed with other waste fractions to homogenise the feed composition. Following pre-treatment, the waste is incinerated according to European requirements: at a minimum temperature of 850 °C or at 1100 °C if the hazardous waste contains more than 1 % of halogenated organic substances, expressed as chlorine (Directive 2000/76/EC).

Heat and electricity are recovered from the hot flue gases by means of a boiler. An air pollution control (APC) system is installed downstream of the boiler for

the removal of particles, acid gases, oxides of nitrogen and dioxins. Heavy metals (e.g., antimony contained in PET) are largely distributed between the bottom ash that arises from the combustion step and the fly ash that is retained by the particle separation systems (van Velzen, Langenkamp 1996; Vehlow 2015). Acid gases, such as hydrogen fluoride, can be removed from the gas phase via wet or dry systems (Vehlow 2015), where alkaline reagents are added to retain the halogens (or sulphur) in solid form (e.g., CaF_2). Finally, the bottom ash and the waste produced by the APC system are classified as hazardous residues and require to be duly handled.

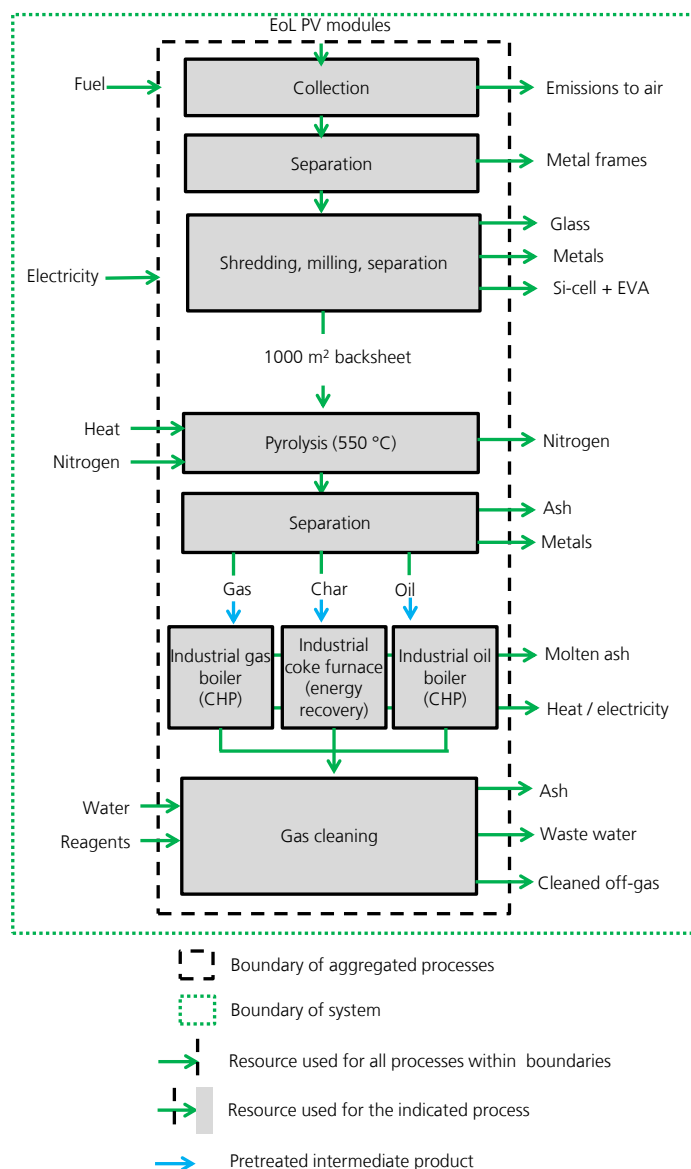
Figure 5-1:
Flow chart for the incineration of both backsheet materials: PET and PVDF.



Pyrolysis of backsheets

For the pyrolysis scenarios (scenario 3.1 and 3.2), the assumptions made for collection and transportation are the same as those considered for incineration scenarios. In addition, the pre-treatment of the waste includes a drying step.

Figure 5-2:
Flow chart for pyrolysis
of PET



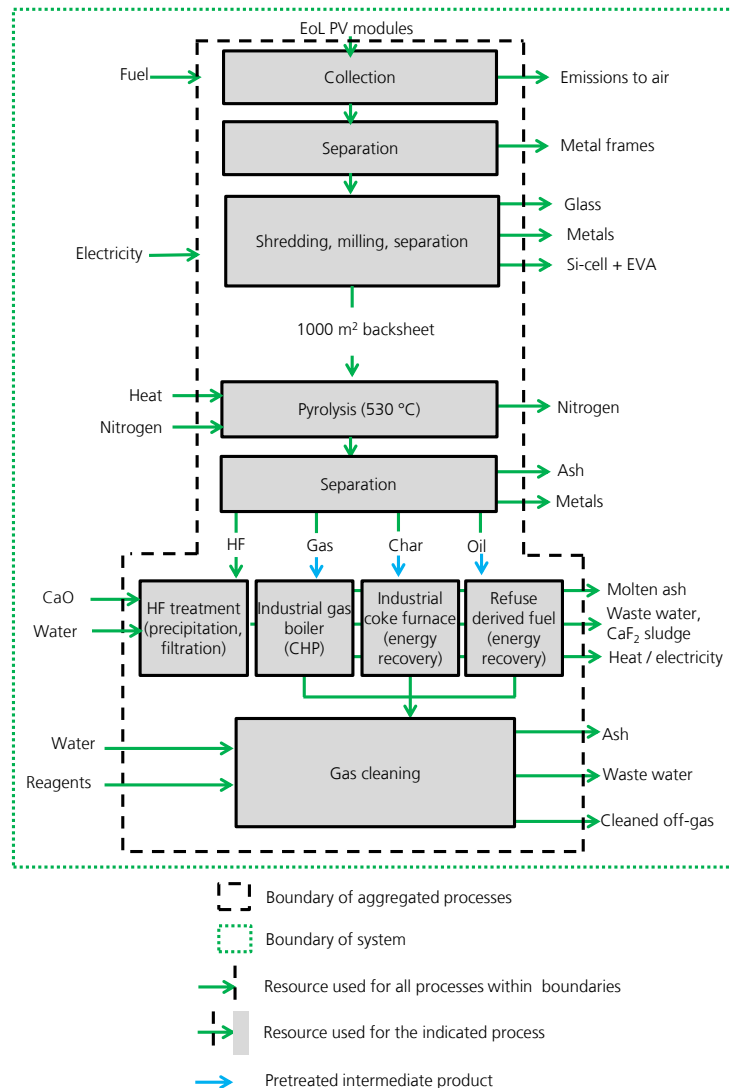
The main processes considered in the pyrolysis of fluorine-free backsheet (scenario 3.1) are shown in Figure 5-2. Firstly, the feed is flash-pyrolysed at 550 °C. Flash pyrolysis of PET produces similar amounts of gas (49 % of the total feed in mass) and oil (39 %) and around 12 % of char (Jung, Fontana 2006; Williams, Williams 1998). The gas fraction is largely composed of CO₂ and CO and, and the oil mainly contain aromatic compounds with oxygen-containing functional groups (e.g., carboxyl, hydroxyl and aldehyde groups) (Williams, Williams 1998).

Energy can be recovered from the pyrolysis products. However, before they can be used, the products need to be treated in order to meet fuel quality requirements. In this model, it was assumed that, after treatment, electricity

and heat are recovered through the combustion of the pyrolysis gas and pyrolysis oil in a cogeneration plant. Heat is recovered via the combustion of the char in a stoker boiler. APC systems are installed in all downstream processes involving energy recovery.

For the pyrolysis of fluorinated backsheet (scenario 3.2) the operations considered are shown in Figure 5-3.

Figure 5-3:
Flow chart for pyrolysis
of PVDF



Firstly, the feed is at first pyrolysed at 530 °C. Here, about 29 % of the feed remains in the solid phase (char) while the remaining part is volatilised (71 %) (Madorsky et al. 1953). The volatile part can be separated into hydrogen fluoride (34 %), pyrolysis oil (37 %) and pyrolysis gas (0.1 %) (Madorsky et al. 1953). It was assumed that the plant equipment is reinforced or lined (e.g., with special alloys) to prevent corrosion by hydrogen fluoride. Following pyrolysis, the hydrogen fluoride is immediately separated from the gaseous phase through a wet system, where an alkaline

additive (CaO) leads to the precipitation of fluorite (CaF₂). The obtained pyrolysis oil and char fractions contain the fluorine in the form of halogenated aliphatic and aromatic compounds (Choi, Kim 2012). Due to their high content of fluorine, these fractions would not meet minimum standards that would be required for their energy or material use.

Nevertheless, it was assumed that, after treatment, energy could be recovered from them when used as refuse derived fuels (RDF) in industrial kilns. However, due to high levels of fluorine, the pyrolysis fractions need to be homogenised for the feed composition to comply with minimum quality standards (e.g., see Rotter et al. (2011)). The pyrolysis gas is combusted in a cogeneration plant, the oil product in an RDF incineration kiln, and the char is combusted in a stoker boiler.

5.1.3 Methodological choices

In this section the main assumptions that affect the results of the LCA study are explained. A quantified uncertainty analysis was not done.

LCA modelling tools

The LCA software GaBi ts 7.3.3 was used in the assessment. For landfilling and incineration scenarios, datasets of processes available in GaBi ts database for waste with a similar composition were used (see section 0). For elements contained in the waste (e.g., C, H, Cl, F, S, N and metals), GaBi waste models use transfer coefficients to estimate how they partition into the different mediums (bottom ash, air pollution control; waste and air in incineration models; gas, water or sludge in landfilling models). In addition, GaBi incineration models consider emissions of compounds that depend on the technologies and operative conditions applied in the incineration plant (e.g., CO, dioxins). For pyrolysis scenarios, processes based on literature data were created by using the mentioned software (see section 0).

5.1.4 Life cycle impact assessment indicators

The midpoint impact assessment indicators included in this study are shown in Table 5-2. The human toxicity and ecotoxicity indicators aim at assessing the adverse impact of pollutants released to the environment on the health of the human population and other living organisms. These indicators are calculated based on a range of variables, but in brief, they are estimated from multiplying the mass of a certain substance emitted to the environment by a factor, which is known as characterisation factor. This expresses the potential increase in the

number of cases of the adverse effect (e.g., cancer). Compared to other indicators widely used in LCA studies (e.g., global warming potential, acidification, eutrophication), which are derived from a well-defined set of compounds and acknowledged characterisation factors, toxicity related indicators need to be estimated for thousands of compounds and the corresponding characterisation factors differ widely due to the numerous variables that determine them (owing to the difficulty in assessing the pathway between exposition to a particular compound and development of the adverse effect) and the multiple models to quantify these variables. Therefore, the toxicity-related results between different scenarios considered in a LCA study tend to differ widely and their interpretation requires caution.

Table 5-2: Impact assessment indicators used in this LCA study

Impact category	Method	Unit
Abiotic depletion (ADP fossil)	CML2001 - Jan. 2016	[MJ]
Acidification potential	CML2001 - Jan. 2016	[kg SO ₂ -eq.]
Eutrophication potential	CML2001 - Jan. 2016	[kg phosphate-eq.]
Freshwater aquatic ecotoxicity potential (FAETP inf.)	CML2001 - Jan. 2016	[kg DCB-eq.]
Human toxicity potential (HTP inf.)	CML2001 - Jan. 2016	[kg DCB-eq.]
Marine aquatic ecotoxicity potential (MAETP inf.)	CML2001 - Jan. 2016	[kg DCB-eq.]
Terrestrial ecotoxicity potential (TETP inf.)	CML2001 - Jan. 2016	[kg DCB-eq.]
Ozone layer depletion potential	CML2001 - Jan. 2016	[kg R11-eq.]
Photochemical ozone creation potential	CML2001 - Jan. 2016	[kg ethene-eq.]
Global warming potential	IPCC 5 th Assessment report, 100 years, excl. biogenic CO ₂	[kg CO ₂ -eq.]
Particulate matter formation	ReCiPe 1.08 Midpoint (H)	[kg PM10-eq.]

5.2 Life cycle inventory and impact assessment

In this section, the life cycle inventory data corresponding to the initial processes that are common to all systems as well as the particular data collected for each scenario are described.

5.2.1 Landfill scenario

Table 5-3 and Table 5-4 show the input and output flows associated with the landfilling of 1 Mg of PET and PVDF in scenarios 1.1 and 1.2 respectively.

Table 5-3: Input and output flows associated with the landfilling 1 Mg PET in scenario 1.1

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	35	Mg	Calculated from mass balance	
Electricity for pre-treatment	215	kWh	Giacchetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection and transportation processes	15.8	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO: Truck PE
Landfilling of PET	1	Mg	Calculated from mass balance	EU-28: Plastic waste on landfill ts
Outputs				
Glass, metals, Si-cell + EVA	34	Mg	Calculated from mass balance	

Table 5-4: Input and output flows associated with the landfilling of 1 Mg PVDF in scenario 1.2

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	28	Mg	Calculated from mass balance	
Electricity for pre-treatment	215	kWh	Giacchetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection and transportation processes	15.8	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO: Truck PE
Landfilling of	1	Mg	Calculated from mass balance	EU-28: Plastic

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
PVDF				waste on landfills
Outputs				
Glass, metals, Si-cell + EVA	27	Mg	Calculated from mass balance	

The electricity demand for shredding and milling an end-of-life photovoltaic module, as well as the electricity required for separating the glass fraction from the semiconductor and polymeric materials by flotation was taken from Giachetta et al. (2013). Both backsheet polymers were assumed to be transported by a truck driven by a diesel engine from the pre-treatment plant to the landfill for non-hazardous waste. The dataset for the landfilling process refers to the environmental impact (uses of resources and emissions) that is allocated to the plastic fraction in a standard landfill for municipal solid waste in Europe. This dataset considers the impact that occurs during the processes of sealing and managing the landfill (treatment of the landfill gas and leachate, and management of the sludge that is produced during the leachate treatment step) over a time period of 100 years (thinkstep GaBi 2017). However, there is in general a lack of information on possible pollutant emissions released from polymers deposited in landfills; e.g., of antimony leached from PET (Snedeker 2014) or fluoride leached from fluoropolymers.

5.2.2 Incineration scenario

As mentioned in section 5.1.2, fluorine-free backsheet waste was assumed to be incinerated in a non-hazardous waste incineration plant (scenario 2.1) while fluorinated backsheet waste was considered to be treated in a plant for hazardous waste. Table 5-5 and Table 5-6 show the input and output flows associated with the incineration of 1 Mg of PET and PVDF in scenarios 2.1 and 2.2 respectively.

Table 5-5: Input and output flows associated with the incineration of 1 Mg PET in scenario 2.1

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	35	Mg	Calculated from mass balance	
Electricity for pre-treatment	215	kWh	Giachetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection,	15.8	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO:

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
transportation and auxiliary processes				Truck PE
Incineration of PET	1	Mg	Calculated from mass balance	EU-28: Polyethylene terephthalate (PET) in waste incineration plants
Outputs				
Glass, metals, Si-cell + EVA	34	Mg	Calculated from mass balance	
Electricity	2.9×10^3	MJ	Calculated	
Heat	6.6×10^3	MJ	Calculated	

Table 5-6: Input and output flows associated with the incineration of 1 Mg PVDF in scenario 2.2

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	28	Mg	Calculated from mass balance	
Electricity for pre-treatment	215	kWh	Giacchetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection, transportation and auxiliary processes	20.2	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO: Truck PE
Incineration of PVDF	1	Mg	Calculated from mass balance	EU-27: Polyvinylidene (PVDF) in waste incineration plants
Outputs				
Glass, metals, Si-cell + EVA	27	Mg	Calculated from mass balance	
Electricity	2.0×10^3	MJ	Calculated	
Heat	4.7×10^3	MJ	Calculated	

The incineration processes in scenarios 2.1 and 2.2 were modelled using generic data from GaBi ts database for an incineration plant for municipal solid waste equipped with technologies that meet European standards. The dataset for the incineration of PET corresponds to the environmental impact that is

attributed to the PET fraction in the considered average municipal waste incineration plant, while the data set for the incineration of PVDF refers to the environmental impact that is allocated to the PVDF fraction. In both datasets, the aspects related to the technologies used in the combustion and APC stages as well as those related to the management of waste are the same: the facility has a moving grate and an APC system that meets European emission regulations and is composed of a selective non-catalytic reduction (SNCR) system for the reduction of NO_x, fabric filters for the reduction of particles, and a dry scrubbing system for the reduction of acid gases. As for the management of the waste, bottom ash is reused as construction material after metal recovery and stabilisation, while fly ash and boiler ash are used for backfilling caverns in salt mines ([thinkstep GaBi 2017](#)). Disposing filter ashes in salt mines is a common management option in Germany, but in most countries this type of ash is landfilled on special landfills ([Vehlow 2015](#)).

5.2.3 Pyrolysis scenario

Table 5-7 and Table 5-8 show the input and output flows related to the pyrolysis of 1 Mg PET and PVDF in scenarios 3.1 and 3.2 respectively. In both scenarios an additional consumption of electricity for washing and drying the feed waste was included.

For scenario 3.1, the mass balance reported by Williams and Williams (1998) for flash pyrolysis of PET at 550 °C in a fluidised bed reactor with nitrogen as the fluidising gas was used. The pyrolysis gas produced has a lower heating value (LHV) of 18 MJ/kg, the pyrolysis oil has an LHV of 28 MJ/kg while the pyrolysis char has an LHV of 30 MJ/kg. The pyrolysis products can be used directly in a gas CHP, diesel CHP and an industrial coke furnace respectively following mild downstream treatment.

Table 5-7: Input and output flows associated with the pyrolysis of 1 Mg PET in scenario 3.1

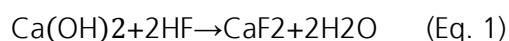
Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	35	Mg	Calculated from mass balance	
Electricity for pre-treatment	300	kWh	Giacchetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection, transportation and auxiliary processes	11.4	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO: Truck PE
Electricity for	130	kWh	Latunussa et al.	EU-28: Electricity

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
pyrolysis			(2016)	grid mix ts
Heat from natural gas for pyrolysis	353	MJ		EU-28: Thermal energy from natural gas ts
Nitrogen for pyrolysis	9.4	kg		EU-28: Nitrogen ts
Outputs				
Glass, metals, Si-cell + EVA	34	Mg	Calculated from mass balance	
Nitrogen	9.4	kg		
Pyrolysis Gas	0.49	Mg		
Pyrolysis Oil	0.39	Mg	Williams and Williams (1998)	
Pyrolysis Char	0.12	Mg		

For scenario 3.2, with the pyrolysis of fluorinated backsheet material, the mass balance determined by Madorsky et al. (1953) for PVDF pyrolysis at 530 °C under vacuum was used, based on the assumption that the process in an atmosphere with nitrogen would result in the same balance. The pyrolysis products include high concentrations of hydrogen fluoride (34 %), poor quality pyrolysis gas with an LHV of 11MJ/kg, pyrolysis oil with an LHV of 11 MJ/kg and pyrolysis char. The pyrolysis oil was found to contain fluorinated hydrocarbons and aromatics and is therefore unfit to use as a fuel. However, it was assumed that, after treatment, energy could be recovered from the pyrolysis oil if used as refuse derived fuels (RDF) in industrial kilns. RDF has a typical LHV of 11 MJ/kg which is very low indeed.

In scenario 3.2, a wet system in the APC system was considered, since wet systems are more efficient to treat highly variable concentrations of acid gases (hydrogen fluoride) in the raw gas (European Commission 2006). Therefore, waste water would be generated, which would require on-site treatment before additional treatment for recovery or disposal (European Commission 2006; Vehlow 2015). In this study, it was assumed that the resulting sludge is disposed of in a landfill.

Furthermore, the content of fluorine in PVDF is about 594 kg F/Mg PVDF or 59 %, which is above the highest limit of the range (50 % of total waste as dry matter) reported for the composition of hazardous waste fed into an incineration plant (European Commission 2006). If about 34 % (in mass) of the feed is estimated to be converted to hydrogen fluoride, posterior conversion of this hydrogen fluoride to CaF₂ demands 629 kg of slaked lime, Ca(OH)₂, (Eq. 1) or 850 kg of lime stone, CaCO₃, considering a stoichiometric ratio of 1.0. If CaCO₃ is used, released CO₂ needs to be stripped off.



This amount of reagent is significantly larger than consumption values reported in the literature: 12-18 kg reagent/Mg waste for current wet air pollution control systems, and 20-30 kg Ca-based reagent/Mg waste for dry systems (Vehlow 2015).

Table 5-8: Input and output flows associated with the pyrolysis of 1 Mg PVDF in scenario 3.2

Mass/energy flow or process	Amount	Unit	Foreground data source	LCI dataset
Inputs				
EoL PV modules	28	Mg	Calculated from mass balance	
Electricity for pre-treatment	300	kWh	Giacchetta et al. (2013) and own estimation	EU-28: Electricity grid mix ts
Diesel for backsheet collection, transportation and auxiliary processes	20.2	kg	Calculated with GaBi ts 7.3.3	EU-28: Diesel mix at filling station ts; GLO: Truck PE
Electricity for pyrolysis	130	kWh	Latunussa et al. (2016)	EU-28: Electricity grid mix ts
Heat from natural gas for pyrolysis	353	MJ		EU-28: Thermal energy from natural gas ts
Nitrogen for pyrolysis	9.4	kg		EU-28: Nitrogen ts
Ca(OH) ₂	629	kg	Calculated considering a stoichiometric ratio 1.0	
Outputs				
Glass, metals, Si-cell + EVA	34	Mg	Calculated from mass balance	
Glass, metals, Si-cell + EVA	27	Mg	Calculated from mass balance	
Nitrogen	9.4	kg		
HF	0.34	Mg	Madorsky et al. (1953)	
Pyrolysis Gas	7.1 x 10 ⁻³	Mg		
Pyrolysis Oil	0.36	Mg		
Pyrolysis Char	0.29	Mg		
CaF ₂ waste (assumed dry)	663	kg	Calculated	

5.2.4 Savings from thermal treatment options

As already pointed out in section 5.1.2, the substitutional effect of energy recovered from thermal treatment is considered, so that the environmental benefits from avoided production and use of fossil fuels are included in the analysis. The lower heating values of the fuels from which energy was assumed to be recovered are shown in Table 5-9.

Table 5-9: Assumed lower heating values of the fuels considered in this LCA study

Scenario	Products	Lower heating value (MJ/kg)	Recovered energy
2.1	PET	22.2	Incinerator: Heat and electricity with steam boiler (44 % net efficiency, 27 % of the output energy is electricity, 73 % is steam)
2.2	PVDF	16.1	Incinerator: Heat and electricity with steam boiler (44 % net efficiency, 27 % of the output energy is electricity, 73 % is steam)
3.1	Pyrolysis Gas	18	Gas CHP: Heat and electricity with gas turbine (< 50 MW)
	Pyrolysis Oil	28	Diesel CHP: Heat and electricity with diesel engine (< 50 MW)
	Pyrolysis Char	30	Coke furnace: Heat with coal stoker boiler
3.2	Pyrolysis Gas	11.2	Gas CHP: Heat and electricity with gas turbine (< 50 MW)
	Pyrolysis Oil	11	Incinerator: Heat and electricity with steam boiler (44 % net efficiency, 27 % of the output energy is electricity, 73 % is steam)
	Pyrolysis Char	30	Coke furnace: Heat with coal stoker boiler

The datasets used to assign credits for energy recovery for scenarios 2.1 and 2.2 is shown in Table 5-10.

Table 5-10: GaBi ts datasets used to assign credits for energy recovery for scenario 2.1 and 2.2

Scenario	Energy flows	GaBi dataset
2.1	Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
	Electricity credit	EU-27: Electricity grid mix (for credit) ts

Scenario	Energy flows	GaBi dataset
2.2	Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
	Electricity credit	EU-27: Electricity grid mix (for credit) ts

The datasets used to assign credits for energy recovery for scenarios 3.1 and 3.2 is shown in Table 5-11

Table 5-11: GaBi ts datasets used to assign credits for energy recovery for scenario 3.1 and 3.2

Scenario	Product	Energy flows	GaBi dataset
3.1	Pyrolysis gas	Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
		Electricity credit	EU-27: Electricity grid mix (for credit) ts
	Pyrolysis oil	Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
		Electricity credit	EU-27: Electricity grid mix (for credit) ts
	Pyrolysis char	Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
	3.2	Pyrolysis gas	Heat credit
Electricity credit			EU-27: Electricity grid mix (for credit) ts
Pyrolysis oil		Heat credit	EU-27: Thermal energy from natural gas (for credit) PE
		Electricity credit	EU-27: Electricity grid mix (for credit) ts
Pyrolysis char		Heat credit	EU-27: Thermal energy from natural gas (for credit) PE

5.3 Results and interpretation

The life cycle impact assessment results obtained in the LCA study are summarised in the following tables (Table 5-12, Table 5-13 and Table 5-14). The impact associated with the treatment stages contributed most to the final results shown in these tables. The contribution of transport processes was very low for all scenarios. These results show the midpoint impact assessment.

For landfilling scenario (Table 5-12) the impacts are the same for both PET and PVDF backsheets materials. Since both of these materials are stored in a closed landfill with no contact to the external environment.

Table 5-12: Results obtained for scenarios 1.1 (Landfilling fluorine-free backsheets) and 1.2 (Landfilling fluorinated backsheets); FU: functional unit 1 000 m² t backsheets material

Impact categories	Unit per FU	Landfilling
Abiotic depletion (ADP fossil)	[MJ]	2980
Acidification potential	[kg SO ₂ -eq.]	0.64
Eutrophication potential	[kg phosphate-eq.]	0.26
Freshwater aquatic ecotoxicity potential (FAETP inf.)	[kg DCB-eq.]	0.93
Human toxicity potential (HTP inf.)	[kg DCB-eq.]	2
Marine aquatic ecotoxicity potential (MAETP inf.)	[kg DCB-eq.]	18 700
Terrestrial ecotoxicity potential (TETP inf.)	[kg DCB-eq.]	10
Ozone layer depletion potential	[kg R11-eq.]	7.40E-08
Photochemical ozone creation potential	[kg ethene-eq.]	0.07
Global warming potential	[kg CO ₂ -eq.]	217
Particulate matter formation	[kg PM ₁₀ -eq.]	0.56

For scenarios 2.1 and 2.2 (incineration) and scenarios 3.1 and 3.2 (pyrolysis) (see Table 5-13, Table 5-14), the lowest value of impact generated from the EoL treatment of the backsheets materials are highlighted in green. For most impact categories, incineration and pyrolysis scenarios of fluorine-free (PET) backsheets material indicate lower impact values than the fluorinated backsheets material (PVDF).

Table 5-13: Results obtained for scenarios 2.1 and 2.2 FU: functional unit, 1 000 m² backsheet material

Impact categories	Unit per FU	Scenario 2.1 Incineration – PET	Scenario 2.2 Incineration – PVDF
Abiotic depletion (ADP fossil)	[MJ]	-3 359	-2 576
Acidification potential	[kg SO ₂ -eq.]	-0.30	9
Eutrophication potential	[kg phosphate-eq.]	-0.02	2.51E-03
Freshwater aquatic ecotoxicity potential (FAETP inf.)	[kg DCB-eq.]	-0.14	32
Human toxicity potential (HTP inf.)	[kg DCB-eq.]	-5	19 458
Marine aquatic ecotoxicity potential (MAETP inf.)	[kg DCB-eq.]	-10 368	278 240 000
Terrestrial ecotoxicity potential (TETP inf.)	[kg DCB-eq.]	-0.07	0.05
Ozone layer depletion potential	[kg R11-eq.]	-9.54E-08	-8.36E-08
Photochemical ozone creation potential	[kg ethene-eq.]	-0.03	-0.02
Global warming potential	[kg CO ₂ -eq.]	572	464
Particulate matter formation	[kg PM10-eq.]	-0.08	-0.02

When comparing incineration scenarios, scenario 2.1 shows lower impact values than scenario 2.2 for all impact categories except for global warming potential. This is related to the elemental composition of the considered polymers: PET has a higher content of carbon than PVDF. Especially in the areas of toxicity thermal treatment of fluorinated backsheets are detrimental to human health and the environment from model estimations.

As for pyrolysis scenarios, scenario 3.1 in comparison with scenario 3.2, indicates lower impact values for most categories. Furthermore, it could be noted that the magnitude of difference (absolute values) between both scenarios for the categories - eutrophication potential, photochemical tropospheric ozone formation potential and particle formation potential is comparatively very small.

Table 5-14: Results obtained for scenarios 3.1 and 3.2 FU: functional unit, 1 000 m² backsheet material

Impact categories	Unit per FU	Scenario 3.1 Pyrolysis – PET	Scenario 3.2 Pyrolysis – PVDF
Abiotic depletion (ADP fossil)	[MJ]	-6 264	-3 097
Acidification potential	[kg SO ₂ -eq.]	4	6
Eutrophication potential	[kg phosphate-eq.]	0.56	0.13
Freshwater aquatic ecotoxicity potential (FAETP inf.)	[kg DCB-eq.]	0.57	15
Human toxicity potential (HTP inf.)	[kg DCB-eq.]	33	7 144
Marine aquatic ecotoxicity potential (MAETP inf.)	[kg DCB-eq.]	48 600	101 050 000
Terrestrial ecotoxicity potential (TETP inf.)	[kg DCB-eq.]	0.14	1
Ozone layer depletion potential	[kg R11-eq.]	-1.68E-07	6.58E-08
Photochemical ozone creation potential	[kg ethene-eq.]	0.22	0.14
Global warming potential	[kg CO ₂ -eq.]	61	620
Particulate matter formation	[kg PM10-eq.]	1	0.86

Therefore, in conclusion pyrolysis could be a potential EoL treatment option for fluorine-free backsheet. However pyrolysis is not a viable option for fluorinated backsheets due to high amounts of hydrogen fluoride (HF) produced during the process in the volatile phase.

Furthermore, the oil phase also contains fluorinated hydrocarbons and thus poses a potential environmental hazard. Therefore, the oil produced from fluorinated backsheet has to be subsequently incinerated in a rotary kiln or alike as a RDF (refuse derived fuel) and is technically unfit for use as fuel in automobiles. It should also be noted that the pyrolysis oil from the fluorinated backsheet material with its high fluorine cannot be readily burnt as such, and therefore must be co-fired with other RDFs to adhere to local emission (of Halogens) regulations.

5.3.1 Contribution analysis of the thermal treatment options

Figure 5-4, Figure 5-5, Figure 5-6 and Figure 5-7 show detailed contribution analysis of various stages along the End-of-Life treatment pathway. The stages

typically include collection and transportation of PV waste material to pre-processing and to final incineration/pyrolysis. The impact of each stage is quantified against the chosen impact categories.

Figure 5-4:
EoL contribution
analysis – Scenario 2.1,
PET incineration

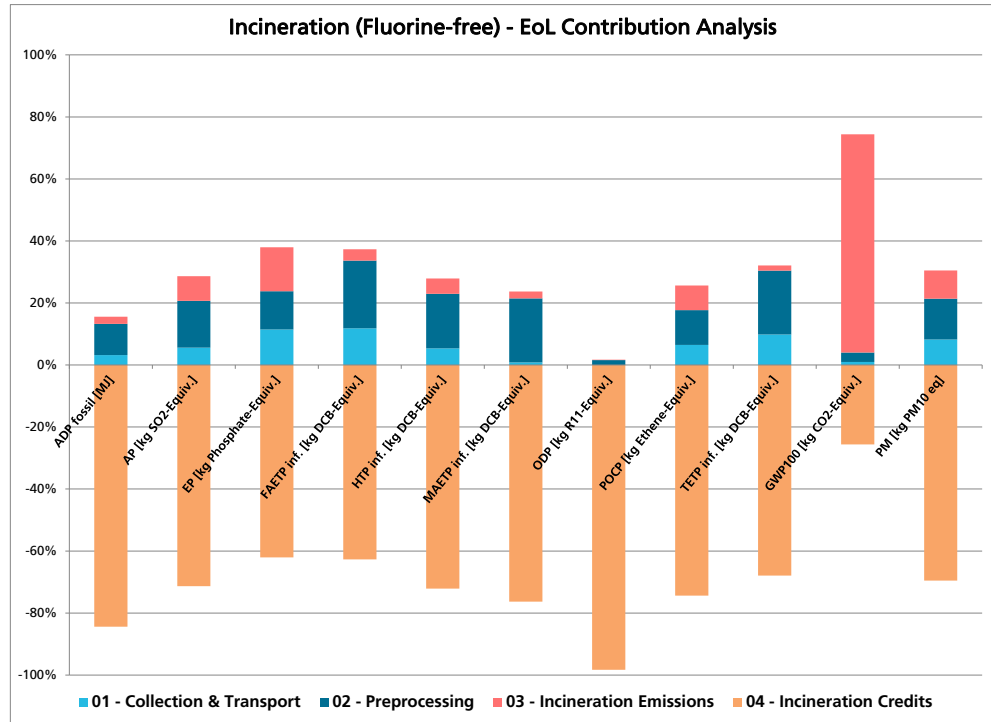


Figure 5-5:
EoL contribution
analysis – Scenario 2.2,
PVDF incineration

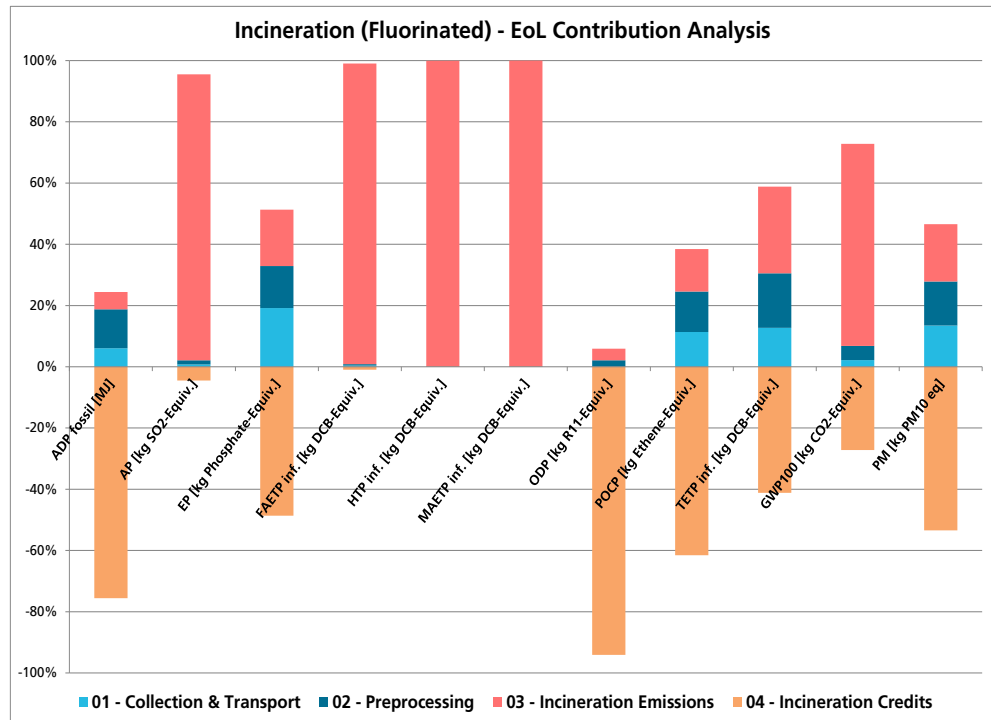


Figure 5-6:
EoL contribution
analysis – Scenario 3.1,
PET pyrolysis

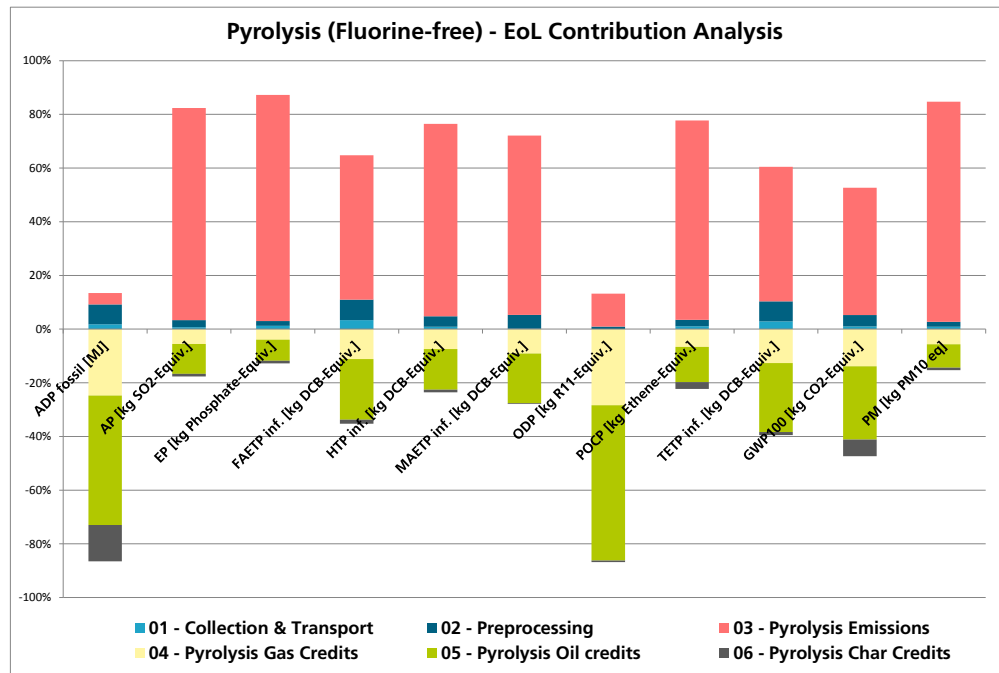
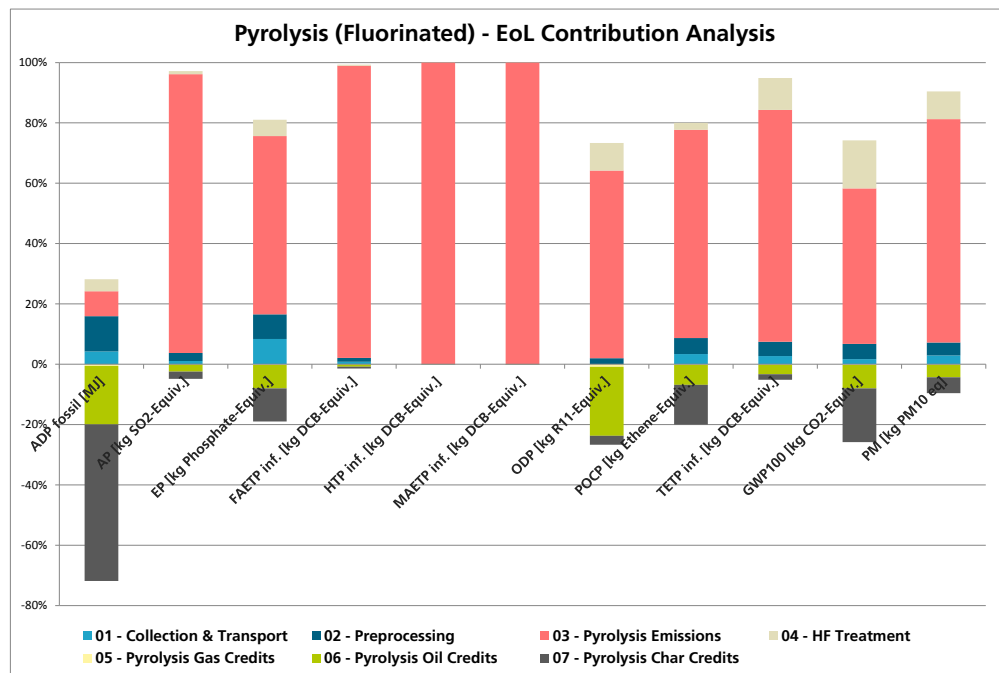


Figure 5-7:
EoL contribution
analysis – Scenario 3.2,
PVDF pyrolysis



6 Conclusions and summary

The results obtained in this LCA study should be interpreted taking into account the main assumptions and limitations:

- (1) For the treatment facilities, only the impact occurring during the operational phase is considered. The treatment of waste fractions other than the primary backsheet material was not included in the analysis (section 5.1.1).
- (2) The composition of backsheet waste was simplified to reflect only the primary material (section 5.1.2). In reality a configuration of these backsheet materials such as PPE, TPT, KPK, etc. are used. This includes other material layers such as adhesives, EVA and primer.
- (3) According to the EU legislation, thermal treatment of hazardous waste whose management is assigned to the industrial producers needs to be performed in plants dedicated for hazardous waste (section 5.1.2). In incineration plants, the feed waste is typically homogenised to comply with the emission standards. The dataset considered for incineration of fluorinated-backsheet waste (modelled as PVDF) reflects the relative environmental impact of that particular waste fraction in an incineration plant for municipal waste.
- (4) Due to a lack of detailed information on the composition of the pyrolysis products (for e.g. hydrocarbons) in scenarios 3.1 and 3.2, the impact associated with the energy recovery systems shows in fact the impact related to the combustion of the replaced fossil fuels in such systems (section 0).

As for fluorine-free backsheet waste, incineration and pyrolysis scenarios obtain similar impact assessment results. The results obtained in both scenarios were clearly better compared to the fluorinated backsheets in majority of the impact indicators.

The incineration of fluorinated backsheet showed a more negative environmental evaluation than the incineration of fluorine-free backsheet across all impact categories except for global warming potential. The relatively higher value for global warming potential is due to the fact that PET molecule contain a higher amount of carbon than PVDF molecule.

Pyrolysis of fluorinated backsheet appears not to be feasible both from economic standpoint and the technical pyrolysis product application point-of-view. The treatment of the hydrogen fluoride present in the pyrolysis gas would

demand a large amount of alkaline reagent and water, as well as a large effort for treating the effluent and the waste. Furthermore, the pyrolysis oil and pyrolysis char fractions obtained as pyrolysis products also contain high amounts of fluorine (both in the form of halogenated hydrocarbons and aromatics), which renders their posterior application for energy recovery unsuitable due to toxicity hazards.

Finally, the results obtained in this study consider a simplified composition and model assumptions. Actual emissions may differ because of complex chemical reactions between the studied polymers and other compounds. Further research (both experiments and LCA) is needed to characterise and assess the thermal degradation of fluoropolymers.

Recommendations for stakeholders involved in the supply chains of photovoltaic modules

In order to meet the demands set by the European Union WEEE Directive (Directive 2002/96/ EC) and the revised WEEE Directive of 2014 requires a coordinated effort across all stakeholders in the photovoltaic industry. Besides the collection, treatment and monitoring of the existing and incoming PV waste, other proactive measures for the future production of PV modules should be highly encouraged in order to reduce the environmental impact of newly produced PV modules in the future.

Some main recommendations for the stakeholders involved in the supply chains of photovoltaic modules are summarised in Table 6-1.

Table 6-1: Recommendations for the stakeholders involved in the supply chains of PV modules. PVI: photovoltaic industry, PVIA: photovoltaic industry associations, PVM: PV manufacturers, EoLMA: end-of-life managers

Stage in life cycle	Recommendation
Designing	Participating in the development of EU standards and regulations on eco-design and eco-labelling. Main stakeholders: PVIA
	Introducing labelling strategies to identify a certain type of backsheets (e.g., fluoropolymer vs non-fluoropolymer) and promoting good practices of extended product declaration (for e.g. Bill of Materials) to facilitate efficient recovery processes and comply with eco-labelling standards. Main stakeholders: PVIA
Manufacturing	Applying eco-design and eco-labelling principles. Main stakeholders: PVM
	Using alternative edge sealants in c-Si modules, easy to release from the modules (Goris et al. 2015). Main stakeholders: PVM
	Using thermoplastic EVA material instead of thermosetting in c-Si modules (Goris et al. 2015). Main stakeholders: PVM

Stage in life cycle	Recommendation
	<p>Avoiding the use of hazardous components. Main stakeholders: PVM</p>
	<p>Minimising the amount of materials per panel: e.g., c-Si panels: glass, polymer, Si, Al, Ag, etc.; CIGS panels: glass, polymer, Al, Cd, Ga, In, Se, etc.; CdTe panels: glass, polymer, CdTe, Ni, etc. (Weckend et al. 2016). Main stakeholders: PVM</p>
	<p>Replacing materials: e.g., substitution or elimination of encapsulant, further optimization of glass composition, thickness, anti-reflective coating, etc. (Weckend et al. 2016). Main stakeholders: PVM</p>
End-of-life management	<p>Increasing voluntary take back schemes. Main stakeholders: PVM</p>
	<p>Scaling up of EoL processing capacity for critical/special component fractions (e.g., polymers). Main stakeholders: EoLMA</p>
	<p>Introducing high collection and recovery targets for PV waste and proportional targets across EU member states (Besiou, Van Wassenhove 2015). Main stakeholders: PVIA</p>
	<p>Providing guidance on updated, best available techniques for waste treatment and waste-to-energy plants. Main stakeholders: PVIA</p>
	<p>Promoting synergies with more mature recycling schemes to create symbiotic manufacturing loops. Main stakeholders: PVIA</p>
	<p>Recovering valuable materials (e.g., Cu, Si, glass, Al, CaF₂), hazardous materials (e.g., HF, Sb, Pb), and energy. Investing in recovery technology (e.g., separation and incineration plants). Main stakeholders: PVMA</p>

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8 Abbreviations

CPE	Coating (fluoropolymer)-PET-EVA
CIGS	Copper Indium Gallium Selenide panel
DOPA	Double Oven Pipe Analysis
EoL	End-of-Life
ELCD	European Reference Life Cycle Data System
EU-27	EU-27 member states
EVA	Ethylene-vinyl-acetate
GHG	Greenhouse Gases
KPE	Kynar®- PET- EVA
KPK	Kynar®- PET- Kynar®
LCA	Life Cycle Assessment
PET	Polyethylene terephthalate
PPE	Indirect Land Use Change
PV	Photovoltaic
PVDF	Polyvinylidene fluoride
PVF	Polyvinyl fluoride
TPE	Tedlar®- PET- EVA
TPT	Tedlar®- PET- Tedlar®

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11 About Us

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² <http://www.umsicht.fraunhofer.de/en.html>

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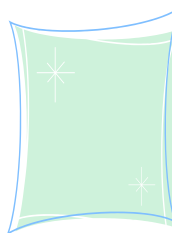
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