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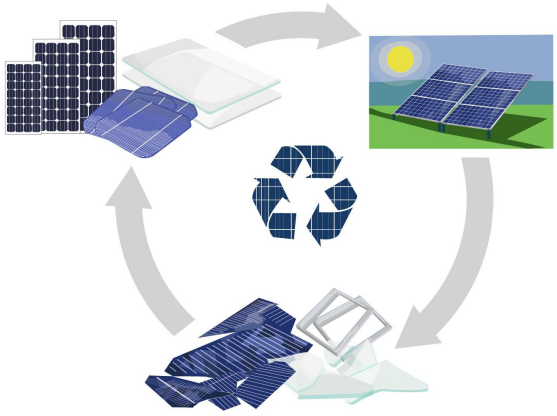
FINAL REPORT

END-OF-LIFE PATHWAYS FOR PHOTOVOLTAIC BACKSHEETS



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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 noticable 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 tothe actual fluorine content measured in the ultimate analyis 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 particluate 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 contamined with hazardous halogened compounds, and thus renders them unuseful for its intended traditional applications without expensive pre-and post-handling methods.

- The LCA for the fluorine-free backsheet show good results compared to the fluorinated backsheet for both incineration and pyrolysis.

- For Incineration, the LCA of fluorinated backsheet shows a more negative environment impact compared to the incineration of fluorine-free backsheet 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 backsheet 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 contains 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 ecolabling standards and thus help the EoL managers in identifying and sorting the toxic fluoropolymer waste from other plastic waste during the EoL treatment PV components.