CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery

Joost R. Duflou (1)*, Jef R. Peeters, Diego Altamirano, Ellen Bracquene, Wim Dewulf (2)

KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, B-3001 Heverlee, Belgium

ARTICLE INFO

Keywords:
Recycling
Optimization
Photovoltaic panels

ABSTRACT

Predictive models to forecast the volume and material composition of end-of-life photovoltaic (PV) panels indicate that substantial material resources can potentially be recovered from silicon based PV panels in the next decades. The technical feasibility of selective mechanical delamination through milling and cleaving was experimentally studied. The achievable material recovery results are compared to current practices in end-of-life treatment, demonstrating a substantial potential to improve resource preservation. A comparative LCA study allows to conclude that a well-designed demanufacturing strategy based on selective delamination can substantially reduce the environmental impact associated with end-of-life processing of PV panels. The improved silver recovery offers perspectives for the economic viability of the described demanufacturing strategy.

1. Introduction

1.1. End-of-life treatment needs for photovoltaic systems

As part of the trend towards renewable energy generation, considerable investments have been made in photovoltaic (PV) systems over the past decades, both by enterprises and private households. Based on the expected functional lifetime of such installations, several authors have predicted the volumes of PV panels that will require end-of-life (EOL) treatment in the years to come [1–3]. Using the distribution delay forecasting method, and taking into account the technological evolution of PV panels in terms of material composition, Peeters et al. [4] developed a predictive model that allows to anticipate the different material mass flows in EOL PV streams. Using the statistics of recently collected EOL PV panels for the example of the Flemish region in Belgium to calibrate this model, an EOL mass stream of crystalline silicon (c-Si) based PV panels increasing to 23,000 ton per annum, equal to 3.4 kg per capita, is anticipated.

While other technologies are visible in the PV market today, c-Si based panels have been dominant and are expected to dominate the EOL treatment scenarios for the coming decades. The results of the predictive model of Peeters et al. [4], as summarized in Fig. 1, are prone to some uncertainty due to the high sensitivity of the predictions to the material composition, the anticipated failure rates and the future material prices. However, some major conclusions can still be drawn from this study with respect to the strategic importance of the respective material fractions and their embodied economic and environmental importance. As visible in Fig. 1b and c, the relevance of the silver, aluminium and glass fractions must be taken into account when determining well-designed methods for EOL PV panel treatment.

Looking at the c-Si PV panel architecture that will dominate the EOL treatment activities in the coming two decades, the layer structure depicted in Fig. 2 is rather constant: embedded between two layers of Ethylene Vinyl Acetate (EVA), the silicon solar cells are coated with metallization paste containing silver and aluminium, and interconnected by silver coated copper bus bars. A layer of antimony containing, low Fe hardened glass guarantees long term physical protection and optimal light transmission. To the non-illuminated side a polymer layer, typically PET based, completes the sandwich structure. The PV panels are often finished and mounted by means of an aluminium frame, and a junction box glued to the backside contains the electronic components to connect the solar cell chains to the PV network.

1.2. State-of-the art in EOL treatment of silicon based PV panels

Driven by the recast Waste of Electric and Electronic Equipment (WEEE) Directive 2012/19, in the EU EOL c-Si PV panels are currently typically processed in general recycling plants, together with other WEEE or laminated glass [5,6]. The materials are separated by means of size-reduction with a hammer mill or shredder, followed by magnetic and eddy-current separation. Only the glass, aluminium, copper and steel fractions are recovered, while the solar cells and plastics containing residue is incinerated or landfilled. The resulting secondary material quality is rather low due to impurities, limited separation efficiencies and presence of

* Corresponding author.
E-mail address: joost.duflou@kuleuven.be (R. Duflou).

https://doi.org/10.1016/j.cirp.2018.04.053
0007-8506/

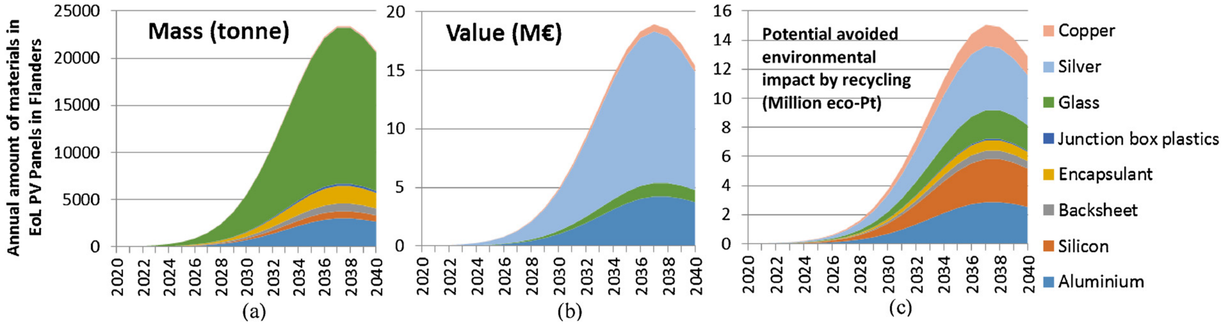

Fig. 1. Predicted mass volumes for EOL silicon based PV panels for the example of the Flemish region of Belgium (a), potential economic value at 2017 material prices for assumed cost free recovery without quality losses (b) and corresponding maximum potentially avoidable environmental impact by closed loop material retrieval for assumed impact free recovery replacing virgin material production (c).

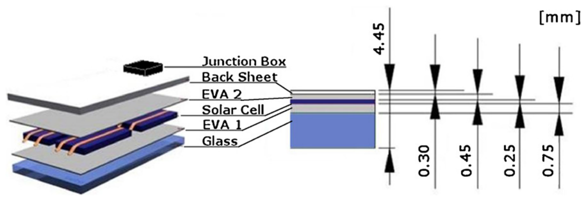

Fig. 2. Typical layer structure of silicon based PV panel with indication of common dimensions (varying between manufacturers and types).

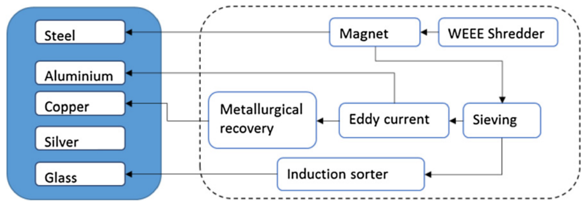

Fig. 3. Baseline scenario: current industrial practice PV panel processing in WEEE treatment plant.

hazardous compounds [7]. In terms of mass recovery rate this treatment method allows to meet the WEEE directive requirements, but results in low value retrieval, and critical materials, such as silver and antimony, as well as the silicon metal are typically not valorised [8]. The glass recovered from c-Si panels is still heavily contaminated with silicon, polymers and metals. However, it can be blended with other recycled glass and used as thermal insulating material in the glass-foam or glass-fibre industries [3].

Besides the conventional mechanical recycling method, various strategies have been explored to achieve the delamination of the so-called 'PV-sandwich', including pyrolysis [9,10] and the use of organic solvents [11,12] to respectively thermally break down or chemically dissolve the EVA encapsulant. A number of patents have also been filed with respect to chemical end-processing of the solar cells to recover the silver [13]. Komoto et al. [13] also identified a number of controlled mechanical separation techniques that are comparable to the processing methods described in Section 2.3 of this article.

1.3. Objectives and scope

The diversity of proposed EOL processing methods for c-Si PV panels, resulting in a wide range of material recovery rates and purity levels, requires a detailed comparative assessment in order to determine the most advisable EOL treatment procedure. In this study both data as reported in literature and experimentally determined material recovery results have been used for this purpose.

2. Comparative study: scenario specifications

Three principal treatment methods have been compared: the process steps included in the respective procedures are summarized in the following subsections.

2.1. Baseline scenario: destructive separation

The commonly used separation procedure, as applied in most recycling plants today, is summarized in Fig. 3. No preliminary removal of the junction box or aluminium frame is considered. A material flow analysis was conducted for this scenario by sampling experiments at a WEEE treatment plant in the Flemish region of Belgium.

The glass fraction recovered from this baseline scenario is highly contaminated with uncontrolled impurities (almost 10% of the glass fraction mass), limiting the useful applications for this fraction and preventing valorisation of the embedded antimony. The copper recovery in the baseline scenario is limited (34,7%) due to imperfect separation and liberation. The silver resources are lost since the recovery is not considered economically viable for the expected concentration present in this fraction (see Table 1).

Table 1
PV waste material composition.

Panel part	Material fraction	%	kg/tonne of PV waste
Frame	Aluminium	14.7%	147.0
	Steel	8.65%	86.5
Junction box & cable	Copper	1.90%	19.0
	Plastic	2.85%	28.5
Encapsulant	Ethylene-vinyl acetate (EVA)	4.52%	45.2
Backsheet	Polyethylene terephthalate (PET)	1.91%	19.1
Front glass	Glass	59.51%	595.1
Solar cell	Silicon	1.82%	18.2
	Aluminium	2.01%	20.1
	Copper	1.99%	19.9
	Silver	0.12%	1.24

2.2. Thermal and chemical treatment scenario

This scenario, as described in detail by Park et al. [14] and summarized in Fig. 4, consists of a pyrolysis treatment at around 400 °C to break down the polymers (EVA and back sheet) and

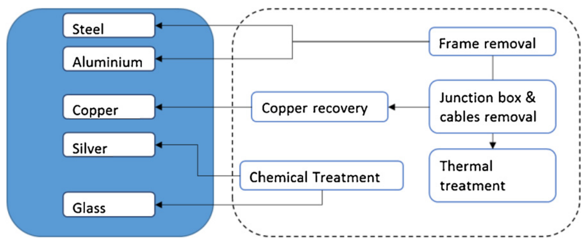

Fig. 4. Thermal and chemical treatment scenario [14]: overview.

Please cite this article in press as: Duflou JR, et al. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.053