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Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels

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ABSTRACT

Lifecycle impacts of photovoltaic (PV) plants have been largely explored in several studies. However, the end-of-life phase has been generally excluded or neglected from these analyses, mainly because of the low amount of panels that reached the disposal yet and the lack of data about their end of life. It is expected that the disposal of PV panels will become a relevant environmental issue in the next decades. This article illustrates and analyses an innovative process for the recycling of silicon PV panel. The process is based on a sequence of physical (mechanical and thermal) treatments followed by acid leaching and electrolysis. The Life Cycle Assessment methodology has been applied to account for the environmental impacts of the process. Environmental benefits (i.e. credits) due to the potential productions of secondary raw materials have been intentionally excluded, as the focus is on the recycling process. The article provides transparent and disaggregated information on the end-of-life stage of silicon PV panel, which could be useful for other LCA practitioners for future assessment of PV technologies. The study highlights that the impacts are concentrated on the incineration of the panel's encapsulation layers, followed by the treatments to recover silicon metal, silver, copper, aluminium. For example around 20% of the global warming potential impact is due to the incineration of the sandwich layer and 30% to the post-incineration treatments. Transport is also relevant for several impact categories, ranging from a minimum of about 10% (for the freshwater eutrophication) up to 80% (for the Abiotic Depletion Potential – minerals).

1. Introduction

Photovoltaic (PV) is one of the renewable technologies that has been gaining importance globally in the last decade. The International Energy Agency (IEA) estimates a total installed power of PV of around 136.5 GW at the end of 2015 [1]. Among the different technologies, crystalline-silicon PV technology still dominates the market, accounting for 85–90% of the technology share [2].

Europe still holds the biggest PV installed capacity, representing 70% of the total installed capacity worldwide [3]. The annual PV Installation in Europe rose from 58 MW/year in 2000 up to 10,975 MW/year in 2013 [3]. In 2012, the electricity produced from PV technology in the European Union (EU) accounted for 2.2% of the total electricity generation [4]. This rapid increase has been largely boosted by European policies and regulations. For example, the European Union (EU) strategy for climate and energy that imposes member states to achieve a target of 27% of the share of renewable energy to be consumed in the EU by 2030 [5].

Given the quantity of the already installed PV panels and its predicted growth, the amount of waste PV panel is estimated to reach 9.57 million tonnes in 2050 [6]. The recycling of waste PV panels will represent a challenge for waste treatment plants in the future. Difficulties related to the end-of-life (EoL) management of the panels (including dismantling of the plant, collection and transport) will be higher and higher, especially considering the large heterogeneous distribution of panels at urban scale [7].

However, the issue on how to properly treat the PV waste raised public attention only recently. For example, the first version of the EU Directive on the "waste of electric and electronic equipment (WEEE)" in force until 2012 excluded PV waste from its scope [8]. In the recast of 2012, the new Directive 2012/19/EU included PV among the list of electric and electronic equipment (EEE) which requires dedicated treatment at their EoL [9]. As regards to the minimum requirements for the treatment of PV panels, the European Commission (EC) also recently requested the European Standardisation Organisations to develop specific

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standards for the treatment of WEEE, which are still under development [10].

Several reasons can be related to this late inclusion of PV waste within the waste legislation and, in general, to the low attention to the potential burdens of the EoL of PV. First of all, PV panels have a potential very large lifetime, up to 25–30 years [11]. Therefore there was a limited interest into investigating EoL aspects so far.

Secondly, the amount of waste PV panels reaching the recycling facilities nowadays is still negligible compared to the amount of other WEEE [6]. Current WEEE recyclers have not yet developed the know-how to process such new waste. According to our interview with two recyclers in Italy, the amount of waste PV reaching their plants is in the order of few panels per month, which are partially dismantled and then treated, together with other WEEE (i.e. by shredding plus post-shredding sorting), without any dedicated plant.

Moreover, policy makers have been trying to promote the diffusion of PV technologies in the last years. In this context, the setting of mandatory requirements for the EoL treatment could have been seen as an obstacle to the effective uptake of this emerging technology.

Furthermore, the lack of scientific evidences about the potential impacts and benefits related to the PV waste treatment did not stimulate policy makers to intervene. As declared by some authors (e.g. by [12,13]), the EoL phase was generally excluded from the studies on the lifecycle of PV technologies because the installations were relatively new and no data or few information were available, mainly referring to small-scale recycling processes. Other studies roughly assimilated the impact of PV recycling to the recycling of other products, as automobiles [14].

However, a study by BioIS [6] already highlighted potential environmental problems related to the improper disposal of waste PV panels, as: leaching of hazardous substances (as lead and cadmium), losses of conventional material resources (as aluminium and glass), and losses of precious and scarce metals (as silver, gallium, indium, germanium). The recast of the WEEE Directive in 2012 intended to regulate this aspect and avoid such future environmental problems to occur. As highlighted by the PV-cycle, the largest pan-European Producer scheme for solar technologies, under the WEEE Directive "PV companies will not only have to ensure the collection and recycling of their discarded EoL products but are required to also guarantee the financial future of PV waste management" [15].

In the last years the interest upon new technologies for the PV panels recycling raised, as proved by the innovative treatments developed by 'Deutsche Solar' for the recycling of crystal silicon panels, and by 'First Solar' for the recycling of cadmium-telluride (CdTe) panels [6].

However, a detailed analysis of the impacts related to such treatments in a lifecycle perspective is still missing in the literature.

A recent research project has been financed by the EU "LIFE programme", titled "Full Recovery End of Life Photovoltaic project–FRELP", aiming at maximising the recycling of the different material fractions embodied into silicon PV panels [16]. This project was developed during the period 2013–2015 in partnership with "PV Cycle Italy". The FRELP project had the objective of developing an innovative recycling process (successively defined as 'FRELP process') for c-Si PV waste aiming at maximizing the recovery of all the material fractions contained into the panels.

This article aims at applying the Life Cycle Assessment (LCA) methodology, as harmonised by international standards [17], to the process developed by the FRELP project. The objective of the article is to provide detailed information about the EoL of the panels, which could be beneficial both to assess the impacts of the proposed recycling process and also to provide detailed lifecycle inventory data potentially useful for other studies on the LCA of PV panels.

The article first illustrates the analysis of the state of art in the scientific literature of studies about the EoL of PV panels. Successively, the article analyses all the phases of the FRELP recycling process and accounts for the lifecycle impacts following the LCA phases set by the standard ISO 14040 [17].

2. State of art: end-of-life of silicon photovoltaic panels

A first study on the technical and economic feasibility of the recycling of crystalline PV modules was already presented in a photovoltaic technology conference in the 1990s [18]. However, the interest on PV recycling started to rise around one decade later. For example, the study by Fthenakis [19] identified the challenges and the possible approaches for PV recycling in USA, concluding that such recycling was technologically and economically feasible but not without careful forethought.

The methods adopted so far for the recycling of silicon PV panels have been based on physical treatments, chemical treatments or a combination of both. A description of these methods is provided in Table 1. In particular it was noticed that the Ethylene Vinyl Acetate (EVA) is the most commonly used material for a layer placed to protect the components of PV module from foreign impurities, moisture, and mechanical damage [20]. The removal of the EVA encapsulation layer has been recognised as one the most challenging steps in the recycling of crystalline silicon PV panels [21].

A completely different treatment to recycle crystalline-based solar cell into building material has been presented by Fernández et al. [22]. This treatment foresees the incorporation of grinded used solar cell to calcium aluminate cement matrix at maximum 5%.

Nevertheless, all these studies contain very little information about the environmental impacts of the proposed recycling processes. The study of Frisson et al. [23] estimated the energy consumption of a standard PV module (with 125×125 mm multicrystalline silicon cells) compared to a module using recycled wafers. The latter resulted in having 40% lower impacts per kWh of electricity produced. However the study did not provide disaggregated information on the recycling process considered. Klugmann-Radziemska and Ostrowski [26] observed that the acid etching mixtures used for the chemical treatments can contain high amounts of toxic substances (e.g. nitrogen oxides, fluorides and different silicon species), which require costly disposal measures. However, also in this case, no further detail was provided.

On the other hand, the lifecycle environmental impacts due to the production and use of PV technologies have been presented in a number of LCA studies available in the scientific literature, as emphasised by several recent reviews [31–34]. However, these reviews either did not consider at all the EoL stage of the panels, or simply highlighted the lack of information about the decommissioning of the PV plants and the EoL of the panels. In the review of Peng et al. [35] some LCA studies, which partially investigated PV recycling, were reported. In particular, this review reported some draft figures about energy consumption due to PV recycling, as calculated by Wild-Scholten [36]. The report estimated that 250 MJ, 240 MJ and 150 MJ were used for the taking back and recycling of mono-Si, multi-Si and CdTe PV systems, respectively. However the study is not clear in what functional unit was considered for these results.

Frankl et al. [37] studied the production of 1 kWh of electricity by different PV technologies and estimated that decommissioning and disposal of a ground mounted PV plant accounted for only 4% of the lifecycle greenhouse gas emissions. Lower impacts were estimated for other impact categories. However, this study did not