Journal of Cleaner Production 89 (2015) 59–64

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Recovery of valuable materials from end-of-life thin-film photovoltaic panels: environmental impact assessment of different management options

Laura Rocchetti*, Francesca Beolchini

Department of Life and Environmental Sciences, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

ARTICLE INFO

Article history:
Received 7 June 2014
Received in revised form
29 October 2014
Accepted 1 November 2014
Available online 8 November 2014

Keywords:
Photovoltaic panel
CdTe
CIGS
Recycling
Critical elements
Life cycle assessment

ABSTRACT

The present study deals with the management of end-of-life copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) thin-film photovoltaic (PV) panels. We quantitatively compare the impacts and environmental weak points of the recycling processes of such panels, and their disposal in a landfill site. Two scenarios of recycling are considered: conventional and innovative. In the conventional recycling, the modules are crushed, glass is recovered, ethylene-vinyl acetate (EVA) is sent to thermal treatment to gain energy and the residual material is disposed of in a landfill site. Conversely, the innovative recycling option goes beyond conventional technologies and it allows to recover also selenium, indium and gallium from the CIGS panels, and tellurium from the CdTe panels. The potential impacts on the environment are similar for the conventional recycling processes of both the typologies of PV panels. Conversely, the innovative recycling of the CdTe panels creates a net production of environmental credits thanks to the recovery of valuable materials. The innovative recycling of CIGS panels has a higher impact than the recycling of CdTe panels (e.g. 2.5 vs 0.7 kg CO_2-eq., respectively, for global warming potential). In any case, the disposal of end-of-life panels is not advantageous for the environment according to life cycle assessment. Data obtained with the recycling processes currently available suggest that the innovative recycling is environmentally beneficial only for the CdTe panels, due to the very low content of valuable elements in the CIGS panels. More effort should be directed to the development of a pre-treatment that can effectively concentrate the valuable elements. Overall, the results of this study give a quantitative basis to support the recycling of PV panels and the recovery of secondary raw materials like tellurium, indium, gallium and selenium.

1. Introduction

In recent years, the request of energy has become an important issue, as there is a strong need to use energy sources alternative to fossil fuels. Electricity generated from photovoltaic (PV) panels is one of the possible alternatives that meet the global energy demand. With the growth of the market of PV panels (EPIA, 2013), it is expected that in 2035 the total mass of waste PV panels will be about 3,000,000 tons, whereof about 800,000 tons belonging to the cadmium telluride (CdTe) technology, and 45,000 tons to the copper indium gallium selenide (CIGS) technology (BIO Intelligence Service, 2011).

CIGS and CdTe panels belong to the second generation of PV panels, those with thin-film deposits of semiconductors. In the CGIS panels, the semiconductor is copper indium gallium selenide. The major concern is due to indium availability, a by-product of zinc production, used in the CGIS panels and other applications (Fthenakis, 2009). Indium and gallium are included in the list of the critical raw materials for Europe, so their recovery as secondary raw materials is of paramount importance (European Union, 2014). In the CdTe panels, the semiconductor is cadmium telluride. Cadmium is toxic and tellurium is a scarce material, obtained as a by-product of copper, lead, gold and bismuth ores processing (Fthenakis and Anctil, 2013; Fthenakis et al., 2009).

The European Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) has established that PV panels should be recycled and the retrieval of valuable secondary raw materials is encouraged. WEEE represents a source of rare and valuable

---

* Corresponding author. Tel.: +39 71 2204225.
E-mail address: l.rocchetti@univpm.it (L. Rocchetti).

http://dx.doi.org/10.1016/j.jclepro.2014.11.009
0959-6526/

elements, often present at higher concentrations than in the mineral ore (Beolchini et al., 2013; Rocchetti et al., 2013). Therefore, there is a real need to develop effective and sustainable technologies addressed at the recycling of the growing number of end-of-life WEEE. At the moment, quite a few technologies are applied for the recovery of high value materials from thin-film PV panels, as recently reviewed by Giacchetta et al. (2013). The company First Solar has industrialized a process for the recycling of CdTe panels based on hydrometallurgical processes. The European project RESOLVED has developed two processes for the copper indium selenide (CIS) and CdTe panels, based on thermal/wet-mechanical and hydrometallurgical processes. The European project SENSE has developed thermal and chemical treatments for CIGS and CdTe panels, and water jet cutting and chemical treatment for CIGS panels (SENSE, 2008). In a study at laboratory scale, Fthenakis et al. (2006) used hydrometallurgical processes based on leaching, ion exchange separation, precipitation and electrowinning to recover cadmium and tellurium from CdTe panels. A study of Sasala et al. (1996) reports that mechanical treatments based on water blasting and chemical processes followed by precipitation, electroplating or ion exchange were suitable for the recycling of CdTe PV panels.

An approach based on life cycle assessment (LCA) represents a useful tool to quantitatively evaluate the environmental burdens related to processes. LCA has been widely applied to compare the sustainability and environmental performance of the processes aimed at electricity generation by PV panels. In the LCA study of Stoppato (2008), the impacts of the polycrystalline silicon (poly-Si) PV panels were considered. Raugei et al. (2007) focused the attention on the production and use of the CdTe, CIS and poly-Si PV modules. Sherwani et al. (2010) reviewed the scientific studies about LCA on the production of the amorphous-Si (a-Si), monocrystalline (mono-Si) and poly-Si modules. Peng et al. (2013) reported an overview on LCA of the production of the a-Si, mono-Si, poly-Si, CdTe and CIS modules, in terms of the energy payback and greenhouse gas emissions. Less studies report data of LCA applied to the end-of-life PV panels. Berger et al. (2010) carried out an LCA of the processes developed by the European project RESOLVED for the recycling of the CIS and CdTe panels. The LCA within the European project SENSE has been described in a report of the project, focusing the attention on the recycling processes of the CIGS, CdTe and a-Si panels (SENSE, 2008). Held (2009) and Raugei et al. (2012) reported the LCA applied to the recycling of CdTe panels, based on the data gained from First Solar. These studies were applied to the whole processes for the recycling of thin-film PV modules. Conversely, other authors (Giacchetta et al., 2013) have carried out LCA of a single step of the recycling process of CdTe panels, developed with an Italian company that undertakes installation of photovoltaic solutions.

The aim of the present study is to broaden the overview of the management options of end-of-life thin-film PV panels. Besides conventional recycling processes, we take into consideration innovative technologies, that enable to recover also valuable and critical elements like indium, gallium, tellurium and selenium. The objectives are to evaluate the impacts and environmental weaknesses of two innovative recycling processes based on international patents for the CIGS and CdTe panels by means of LCA, and to compare them with conventional recycling and disposal in landfill.

2. Materials and methods

2.1. Management options of end-of-life PV panels

In the present study, the processes aimed at the recycling of glass, selenium, indium and gallium from the CIGS, and glass and tellurium from the CdTe thin-film PV panels were considered. The two processes were based on data found in international patents (US 2002/6391165 B1, WO 2012/068668 A1 and US 1998/5779877) and included mechanical and chemical processes. For both the recycling processes, we considered two scenarios. The conventional recycling, where the modules were crushed, glass was recovered, ethylene-vinyl acetate (EVA) was sent to thermal treatment to gain energy and the residual material was disposed of in a landfill site. The innovative recycling goes beyond the conventional processes: other steps were added to recover also selenium, indium and gallium from the CIGS panels and tellurium and sodium sulfate from the CdTe panels. Sodium sulfate was not a product directly recovered from the panels, but it was formed as a consequence of the process of cadmium and tellurium precipitation. For this reason, in the text it is not cited among the recovered materials.

The innovative recycling for the CIGS panels was based on the following operations: crushing, acid leaching, precipitation, filtration, extraction with surfactant and solvent, and electrodeposition (Table 1). For the CdTe panels, the innovative recycling was based on crushing, acid leaching, precipitation, filtration and electrowinning (Table 2). Furthermore, cadmium was removed from the leaching solution by ion exchange and properly disposed of. Cadmium is not a critical raw material for its supply, and it is generally recovered as a by-product from zinc concentrates (cadmium production is high: about 20,000,000 tons/y; USGS, 2014). Similarly, copper was not a target elements within the innovative recycling process of the CIGS panels. Indeed this element is present at low concentration in the PV panels and it is a non-critical raw material, with a high world production (about 15,000,000 tons/y in the last years; USGS, 2014). Therefore, we did not consider further steps addressed at the recovery of cadmium and copper, thus avoiding the request of energy and raw materials.

2.2. Life cycle assessment

LCA was carried out to compare the impacts on the environment of the conventional and innovative processes aimed at the recycling of the end-of-life CISG and CdTe PV panels, as well as to identify the critical issues for the environment. Furthermore, the two recycling scenarios applied for both the CIGS and CdTe PV panels were compared to disposal in landfill sites. The GaBi 5.0 Professional software integrated with the EcoInvent 2.2 database was used for LCA.

The system boundaries of LCA comprised the management options considered in the present paper: they included the two

Table 1
Main steps for the innovative recycling of 1 m^2 of CIGS panels.

Process	Reagents (g)	Recovered materials
Crushing		
Acid leaching	Sulfuric acid (750) Hydrogen peroxide (23) Surfactant (23)	
Skimming and filtration		Glass EVA
Precipitation and filtration	Sulfur dioxide (75)	Selenium
pH adjustment	Sodium hydroxide (330)	
Indium extraction	D2EPHA (30) Toluene (120)	
Stripping	Hydrochloric acid (750)	
Electrodeposition		Indium
pH adjustment	Sodium hydroxide (105)	
Gallium extraction	D2EPHA (36) Toluene (145)	
Stripping	Sodium hydroxide (900)	
Electrodeposition		Gallium