ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Management of end-of-life photovoltaic panels as a step towards a circular economy

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ARTICLE INFO

Keywords:
Photovoltaic panels
End-life
Waste management
Life cycle
Circular economy

ABSTRACT

Recent trends in the international photovoltaic (PV) sector indicate strong growth in terms of capacity and production, which is positively influencing the process of energy system decarbonisation. The aim of this review was to promote productive paradigms for a 'closed cycle' economy based on the enhancement of resource efficiency and the reduction of waste. To this end, the articulate framework for the management of end-of-life PV panels was analysed, highlighting strengths and weaknesses from the perspective of transitioning towards a circular economy. The conceptual framework is based on a comprehensive review and analysis of relevant literature to describe the main technological and environmental implications associated with PV energy production. Consequently, this paper highlights the most important critical elements, potential opportunities, and limitations deriving from the technological, managerial and organisational aspects of enhancing recovery and recycling rates. The review and the proposed framework might be useful for further research on this important yet complex topic.

1. Introduction

In recent years, the European and international electricity markets have witnessed a formidable growth in the photovoltaic (PV) sector, mainly due to a robust increase in installation capacity and energy production. Global installed PV power reached 310 GW in 2016 [1] and is expected to reach approximately 395 GW by the end of 2017, an increase by 85 GW [2]. In the mid-term (by 2020), the global capacity could triple to 700 GW [3], while in the long term (by 2050), it could amount to 4500 GW [4].

Industrialized countries (including China and India) that have implemented projects to decarbonise their energy systems by taking advantage of solar technology will experience a strong push towards growth in the PV market. The United States has also begun to invest in PV power stations, acquiring a significant global position behind China and Japan [5]. The US has the fastest growth rate in terms of installed capacity among non-European countries.

In addition to the expected price volatility of fuels, factors such as the rising cost of electricity generated by conventional power stations and the sharp decrease in the price of PV modules strongly affect PV growth [6]. The reason for rising cost is the introduction of increasingly restrictive rules on pollutant emissions in some countries, and that for the sharp decrease is decreased production costs and higher performance of solar cells. Although this growth is considered to be essential for a transition to a low-carbon energy scenario, it also brings new challenges, principally related to the economic and environmental sustainability of the entire PV supply chain, especially the end-of-life stage of modules. End-of-life management is an approach to proper management of the treatment of PV wastes. In the near future, end-of-life management for PV modules will play a strategic role in realizing a sustainable PV sector [7]. This involves implementation of suitable recovery and recycling procedures, and adoption of adequate technologies for treating waste derived from the decommissioning of PV power stations.

In Europe, a drive towards responsible end-of-life management for PV modules has taken form in the Directive on Waste Electrical and Electronic Equipment (WEEE; Directive 2012/19/UE of the European Parliament and the Council), according to which decommissioned PV panels are included as domestic and professional types of WEEE. The purpose of this directive is to promote the use of secondary raw materials in order to foster more efficient use of natural resources associated with PV production.

At the end of their life, PV modules are sorted based on the power of their installation facility and the time they entered the market, thus

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http://dx.doi.org/10.1016/j.rser.2017.10.039
Received 22 December 2016; Received in revised form 12 June 2017; Accepted 26 October 2017
1364-0321/

Nomenclature

a-Si	amorphous silicon
Al	aluminium
BOS	balance of system
c-Si	crystalline silicon
Cd	cadmium
CdS	cadmium sulfide
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CIS	copper indium diselenide
CO_2 eq	equivalent carbon dioxide
Cu	copper
DSSC	dye-sensitised solar cells
Ga	gallium
GHG	greenhouse gas
EG-silicon	electronic-grade silicon
EPBT	energy payback time
EVA	ethyl-vinyl acetate
ExternE	external costs of energy
GW	gigawatts
In	indium
kWh	kilowatt-hour
kWp	kilowatt-peak
LCA	life-cycle analysis (or assessment)
mc-Si	multi-crystalline silicon
MG-silicon	metallurgical-grade silicon
m^2	square meter
Mo	molybdenum
mono-Si	mono-crystalline silicon
MW	megawatt
Pb	lead
PV	photovoltaics
Se	selenium
Si	silicon
SoG-silicon	solar-grade silicon
Sn	tin
t	metric tonne
Te	tellurium
Tedlar	back-sheet layer based on Polyvinyl Fluoride
TeO_2	tellurium dioxide
TiO_{2t}	itanium dioxide
Znz	zinc
x-Si	silicon-based panel
W	watt
WEEE	waste electrical and electronic equipment

permitting differentiated processing according to technical and economic criteria. This uses an approach known as 'extended producer responsibility', which now represents one of the most important meta-principles of environmental policy.

According to this environmental policy, manufacturers and producers are considered responsible for the life cycle impacts of their products and, therefore, should be encouraged to carry out new materials and process tests expanding recycling technologies and designing products to be more easily recycled [8].

The goal of this study was to affirm emerging production paradigms designed to promote a 'closed loop' economy based on sharing, leasing, reuse, repair, refurbishment and recycling and, then, on a greater appreciation for energy and natural resources, and the minimisation of waste production. To this end, the contribution of the PV sector to satisfying energy demands was analysed.

PV technologies aim to produce 'green energy' using solar power, which is a renewable, cost-free resource with no atmospheric emissions, such as carbon dioxide and other greenhouse gases. However, during entire life cycle of PV panels, from the production of modules to their ultimate disposal, a considerable amount of non-renewable resources and other energy sources are used, generating pollution and waste with high environmental impacts. To ascertain opportunities available for rendering more efficient end-of-life management of PV panels, this study particularly analysed resource and material flows in the most common types of PV panels. The review focused mainly on analysing case studies on the PV sector.

In view of the fact that research pertaining to the topic of management of solar panel end-of-life is relatively new and under development, our objective was to describe and synthesize the knowledge gained by scientific studies. We focused on the main technological and environmental implications associated with PV energy production and provide the cause for reflecting on means to achieve an even greener photovoltaic energy life cycle. This literature review provides an overview of the management of solar panel end-of-life, and suggests a framework to promote productive paradigms for a 'closed loop' economy. The results of this study will be useful for future studies on end-of-life management of photovoltaic panels.

With regard to the criteria used to critically select papers, in general, we attempted to seek useful papers and information regarding the economic, environmental, and social impacts associated with the entire life cycle of PV panels.

The information provided in the literature was helpful for making projections of assumed use of recycled PV panel wastes used in production and calculating the number of new panels that can be produced by a given number of used PV panels. This aided in assessing the efficiency of "closing the loop" and, therefore, providing an answer to the question of how strongly can we rely on circular economy regarding the PV sector.

Section 2 describes the theoretical background focused on different perspectives of environmental impacts associated with the PV technology. It shows that over time, research on the PV industry will be focused on "hot" issues that characterise not only the energy sector but also the manufacturing sector in general and energy-intensive sectors in particular [9].

The study proceeded with an in-depth analysis of the technological aspects and life-cycle stages of the most common types of PV panels, focusing on the main environmental issues.

We focused on the main critical elements and potential opportunities and limitations derived from the technological, managerial, and organisational options available to enhance recovery and recycling rates of PV panels. Based on the analysis, the main challenges that the photovoltaic sector will face and the role it will play in the transition to a circular economy were analysed.

Section 7 concludes the paper by highlighting the main findings and outcomes of the study.

2. Background

One of the first studies to highlight concerns over the scarcity of natural resources in relation to PV technology focused on assessing energy consumption associated with the production of PV cells [10]. The study emerged when much of the literature was emphasizing the importance of efficient monitoring and reorienting the 'flows of materials and energy' in the context of production processes, especially energy-intensive ones, in order to confront price restrictions arising from oil crises [11].

In successive decades, research focused on analysing environmental performance as it is related to the manufacture of various types of products, including PV cells [12]. This orientation reflects changes in the reference scenario, characterised by growing interest in issues linked to the environmental impact of human activities and the