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Review Paper

End of life silicon based photovoltaic panels: A review

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A B S T R A C T

Solar energy is a clean renewable energy source. During the electricity production, photovoltaic systems do not generate any waste or toxic emissions. However, if this industry is to truly present a sustainable solution it must account for the photovoltaic solar panels' end-of-life phase. According to the already installed PV panels and its predicted growth, the amount of waste PV panel is estimated to reach in 2050, 78 million tons. Different researches showed the necessity to recover the photovoltaic waste panels and according to the last issue guideline of the European Union (2012/19/EU), the end of life photovoltaic panels are considered as electronic and electric equipment waste. In this review paper, different recent researches interest of recycling photovoltaic panels will be cited. The several components, which constitute silicon based photovoltaic panels, will be presented. These silicon based photovoltaic panels presented are realizing in researcher center of technology of semiconductor for energetic (CRTSE, Algeria). The materials present in the panels can be recovered and reused using specific methods; once their modules reach the end of their life cycle such as: glass and aluminum, as well as semiconductor materials such as silicon, copper. Finally, we will cite 53 different recycling panels industries.

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1. Introduction

Up to day, the crystalline silicon is the more use semi-conductor for photovoltaic applications with more than 90% of the total photovoltaic technology as mono or polycrystalline silicon.
The exponential grow of photovoltaic panels highlights the necessity to cope with the environmental impact which could raise from wrong practices for disposal of end of life photovoltaic modules (Fig1.), the amount of waste PV panel is estimated to reach in 2030, 30 million tons (Fig 2.) [1].

Fig 1. Waste PV panel

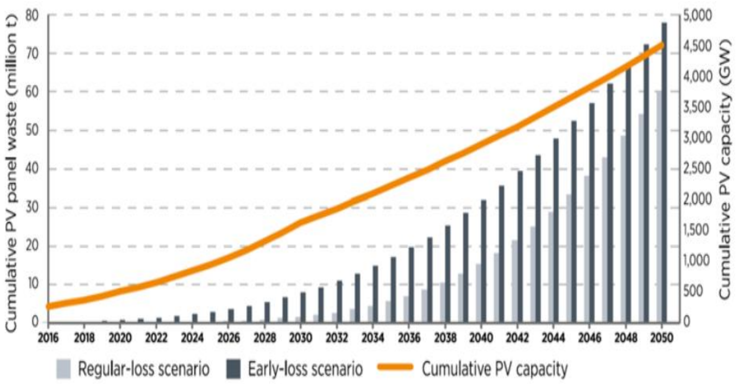

Fig 2. Estimated cumulative global waste volumes of end-of-life PV modules [1].

In fact, their possible disposal in landfills would represent a loss of material and energy, as photovoltaic modules are goods that can become very useful even at the end of their life.

So recovering metals from Si cells is necessary, it can be achieved by chemical approaches such as etching with acid or alkali hydroxide. Another method is a direct treatment by a metal refinery company. With regard to the recycling of compound semiconductors PV modules, a combination process involving mechanical (crushing) and chemical etching is in operation on a commercial scale. However, preparing for the future with regard to waste PV modules, several additional technologies and researches are under development.

This paper aims to provide essential information concerning the conception of silicon based photovoltaic panel; the latest researches interest in photovoltaic recycling panels will be review and finally 53 recycling panels companies will be cite.

2. State of art

PV modules have a technical lifespan of practically 20 to 30 years and will become electronic waste (WEEE) in the future years, since the commencement of broad photovoltaic installation occurred in the 1990s. End-of-life modules are expected to reach 78 million tons by the 2050s [1]. Therefore, it is essential to develop recycling technologies to reduce the amount of this waste; more than 128 patents were identified as pertaining to recycling of c-Si modules [1] and several researches were done in this field taking into consideration the dimensions that it will acquire in the future years. Valeria Fiandra and al presented and discussed the management of end-of-life PV modules based on an advanced eco-sustainable process [2]. Ewa Klugmann-Radziemska discussed in its article the main outcomes and analyses the significance of recycling in relation to the environmental profile of the production and total life cycle of photovoltaic cells and modules [3]. G. Granata and al investigated a recycling of polycrystalline silicon, amorphous silicon and CdTe photovoltaic panels by studying two alternative routes made up of physical operations [4]. Cynthia E.L. Latunussa et al provided transparent and disaggregated information on the end-of-life stage of silicon PV panel [5]. Dávid Strachala et al dealed with methods of recycling of photovoltaic modules and evaluates contribution of recycling to the environment and reduction of raw materials extraction [6]. Yan Xu et al presented a review which provided a quantitative basis to support the recycling of PV panels, and suggested future directions for public policy makers [7]. Pablo Dias et al separated a waste of silicon-based PV modules using an electrostatic separator after mechanical milling [8]. Charlie Farrell et al analysed both used polymers taken from a deconstructed used PV module and virgin-grade polymers prior to manufacture to determine if any properties or thermal behaviours had changed [9]. Idiano D'Adamo et al investigated the financial feasibility of crystalline silicon (Si) PV module-recycling processes [10]. Marina Monteiro Lunardi et al presented a summary of possible PV recycling processes for solar modules, including c-Si and thin-film technologies as well as an overview of the global legislation [11]. Marina M. Lunardi et al undertook an attributional LCA was to compare landfill, incineration, reuse and recycling (mechanical, thermal and chemical routes) of EoL crystalline silicon (c-Si) solar modules, based on a combination of real process data and assumptions [12]. K. Hamouda et al established a program to recover and recycle photovoltaic modules which consider how to minimize recycling cost and recycling process effect on the environment [13]. Songi Kim et al analyzed and compared three real cases of manufacturer's recycling policy, including Deutsche Solar, First Solar, and PV Cycle, from the perspective of a closed-loop supply chain [14]. Meletios Rentoumis et al presented in their article the simulation of an integrated c-Si PV recycling process, applicable to the industrial level, with the use of CATIA software [15]. Cynthia E.L. Latunussa et al illustrated and analysed an innovative process for the recycling of silicon PV panel. The process is based on a sequence of physical treatments followed by acid leaching and electrolysis [16]. Francesca Pagnanelli and al gave a picture of the PV world in terms of market, typology, waste dynamics and recoverable materials [17]. Yang Xu et al discussed the background, causes and the main dealing method of waste photovoltaic (PV) modules [18]. Manivannan Sethurajan et al summarized the recent progress regarding various hydrometallurgical processes for the leaching of critical elements from WEEEs [19]. Youn Kyu Yi et al evaluated the key issues related to PV recycling, aiming to reflect the scenario that the world and in particular, the Korean solar energy industry will face in the future [20]. Maurianne Flore Azeumo and al treated the polycrystalline silicon type photovoltaic modules with a physical and a chemical process [21]. Ornella Malandrino et al carried out a review of the main technical-economic and environmental implications associated with the production of photovoltaic (PV) energy, particularly in Europe and in Italy [22]. Hengky et al, give to readers a compile synthesize reported drivers, barriers, and enablers to EoL management of PV panels and BESS in the context of the circular economy [23]. Svetlana Ratner et al, extended in their study the current knowledge of the environmental impacts of most common renewables throughout the entire life cycle [24]. Sina Herceg et al offer in their study more detailed analysis of different end-of-life approaches for the main photovoltaic technologies that are found on the market [25]. Garvin A. Heath et al suggest in their study that the recovery of high-value silicon is more advantageous than the recovery of intact silicon wafers [26]. Sigrid Kusch-Brandt et al, shed light on the upcoming problem of waste when PV panels reach their end of life phase [27].

Chuang Xu et al, employed in their study a customized ultrasonic instrument and compound solvents to recover backsheets from crystalline silicon PV modules [28]. Sanna-Mari Nevala et al, present in their study, for the first time a comparative analysis on the use of EHF technique and conventional crushing for the processing of PV solar panel waste [29]. C.C. Farrell, provide in their paper guidance for understanding the c-Si PV module manufacturing process and how to best approach the challenge of recycling this vast and inevitable waste stream [30]. Xin Lu et al exhibit in their paper, the efficiency of metallurgical processes for separating most of the impurity elements on silicon wafers issued from end of life photovoltaic panels [31]. Dong, A. et al summarized in their paper, different kinds of silicon wastes during the production of SoG-Si and the beneficial analyses were briefly discussed too for the recycling of SoG-Si wastes [32]. John A. Tsanakas et al introduce on their review study the relevant research groundwork, a status overview and today's R&D and business challenges in PV recycling, repair/refurbishment and re-certification aspects for second-life PV modules [33].

3. Photovoltaic panel structure

The main component of PV module is semiconductor materials (mainly silicon) solid PV cells. A photovoltaic panel (Fig.3) is the combination of PV cells with organic glass, EVA (ethylene/vinyl acetate copolymer), the back, the aluminium alloy layer pressure, junction box. The details of the CRTSE panel components are shown in figures (3-9). Their specific functions and characteristics are as follows:

- The glass:

Solar panels are made of tempered glass (Fig 4.). It protects the main body of power generation against damaging external factors, such as water, vapor, wind and dirt.

- The EVA (Ethylene-Vinyl Acetate):

The Eva is a polymer encapsulating (Fig 5.) of the photovoltaic cells. It protects the photovoltaic module against all environmental changes such as wind, UV radiation; temperature change, etc. The Eva is easily degraded in front of air, and its color will change to yellow, and this degradation will affect its proprieties.

- The cell.

The cell (Fig 6.) is a component which coverts light to electricity; the most used one is silicon.

- The backsheet.

The backsheet (Fig 7.) acts as a moisture barrier and external weather changes. The backsheet material is made of various polymers or plastics including PP, PET and PVF which offer different levels of protection, thermal stability and long term UV resistance.

- Aluminum frame.

The aluminum frame (Fig 8.) supports the main body of the photovoltaic module.

- The junction box.

The junction box (Fig 9.) is a small weatherproof which protects the connections and provide a safety barrier.

Fig 3. Silicon based photovoltaic panel (CRTSE conception)

Fig 4. The glass

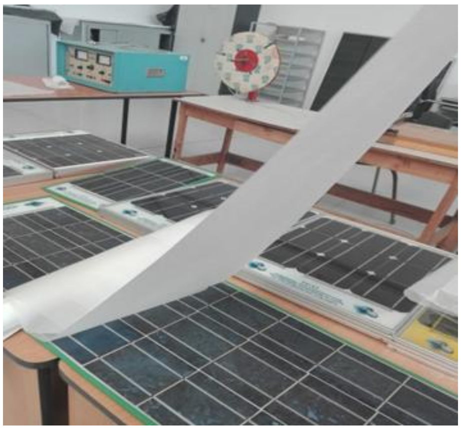

Fig 5. The EVA

Fig 6. The cell

Fig 7. The backseet

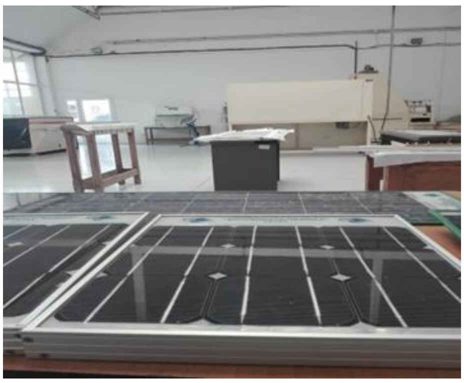

Fig 8. The aluminum frame

Fig 9. The junction box

The composition of PV modules varies according to the used technology. The average composition of a current c-Si module is representing in the table 1, this important quantity of materials can be recycling and reused using different methods. The largest fraction of components material is class and its represent the largest fraction of recovered material which is mainly used in recycled glass industries.

The second material recovered is the aluminum; it's issued from the aluminum frame.

Other materials such silicon from the solar cells, steel and copper from junction box and cable and solar cells can be recovered too. In the Fig 10, the potential of the recovery material under different treatments is illustrated.

Table 1. The average composition of a current c-Si module [34].

Component	Weight %
Glass	74.16
Frame aluminum	10.3
EVA	6.55
Solar cells Backing film	3.48
Junction box	3.6
Adhesive potting compound	1.16

4. Panels recycling industries

Recycling solar panels has a number of environmental benefits. The first is that it creates a useful and sustainable method of disposing of panels that have reached the end of their useful PV lifespan. Recycling solar panels also provides raw materials for repurposing and reprocessing. In Europe, photovoltaic cycle today guarantees average recycling rates between 90 and 97%, in the table 2, 53 companies around the words providing recycling service for solar PV manufacturers were presented. For more information about the type of process used in each company, the web sites were added as bibliographies references.

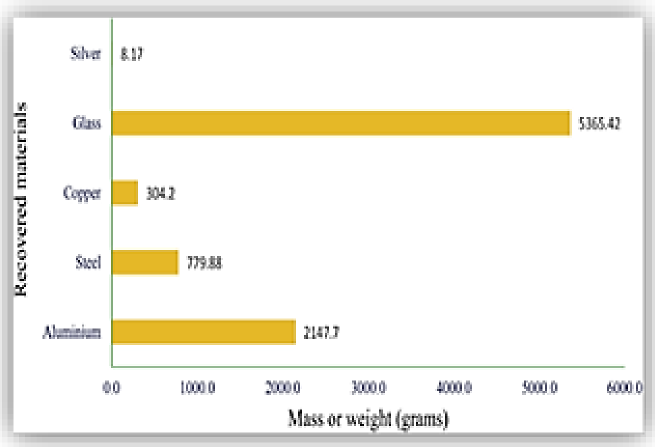

Fig 10. Estimated material recovery potential from end of life silicon based photovoltaic panels [35].

6. Conclusion

Photovoltaic panels contain material substances like glass and aluminium, as well as semiconductor materials such as silicon, copper, indium, cadmium and tellurium which can be recovered and reused once their modules reach the end of their life cycle. Recycling of solar panels can help to recover 80 percent of crystalline silicon and other material substance, for this purpose several patents and researches was developed. As a result, more than 53 recycling panel industries were created so the widespread deployment of solar panel in the past is expected to create a huge opportunity for the recycling business once the panels complete their service life.

5. Acknowledgment

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Table 2. Panel recycling industries

Company name	Localization	Recycling Services	Recycled Products
Aurubis	Germany	Recycled Material Trading	Chemical Elements [36]
Chaoqiang Silicon Material	china	Direct Recycling	Ingot, Wafer [37]
Dynamic Lifecycle Innovations	United States	Direct Recycling	Solar Panels, Cable, Junction Box, Frame [38]
ECS Refining	United States	Direct Recycling	Solar Panels [39]
Eiki Shoji	Japan	Recycled Material Trading	Solar Panels [40]
Elsi	Germany	Recycled Material Trading	Solar Panels [41]
Envaris	Germany	Direct Recycling	Solar Panels,Cable [42]
Euresi	Spain	Recycled Material Trading	Encapsulant, Backsheet[43]
Exotech	United States	Recycled Material Trading	[44]
Experia Solution	Italy	Recycling Equipment, Direct recycling	Solar Panels, Ribbon,Glass,Cable, Junction Box [45]
First solar	United States	Direct Recycling	Solar Panels [46]
Frisetec	Germany	Direct Recycling,	Ingot, Wafer, Cell [47]
Green lights recycling	United States	Direct Recycling	Solar Panels [48]
Gvs	Switzerland	Direct Recycling	Solar Panels [49]
IBA	Hong Kong	Recycled Material Trading	Ingot, Wafer [50]
IMMARK	Switzerland	Direct Recycling	Solar Panels [51]
Infoactiv	Australia	Direct Recycling	Solar Panels [52]
Interco trading	United States	Direct Recycling	Solar Panels, Glass, Junction Box, Frame[53]
Jiangsu Juxin Energy Silicon Technology	China	Direct Recycling	Ingot, Wafer, Cell, Solar Panels, Slurry[54]
Kunshan Aotesi Solar Technology	China	Direct Recycling,	Cell, Solar Panels [55]
Kunshan Hairunder Recycling Management	China	Recycled Material Trading	Wafer, Solar Panels, Ribbon [56]
Kunshan Suda Jingwei Electronic Technology	China	Direct Recycling	Ingot, Wafer, Cell, Solar Panels, Slurry [57]
KWB Planreal	Switzerland	Recycled Material Trading	Solar Panels [58]
La Mia Energia	Italy	Recycling Equipment, Direct recycling	Ingot, Wafer, Cell, Solar Panels, paste [59]
Metal & Catalyst Resources	United States	Direct Recycling	Chemical Elements [60]
Morgen Industries	United States	Direct Recycling	Cell [61]
Panoramic Resources Partners	United Kingdom	Direct Recycling	Solar Panels [62]
PV Techno Cycle	Japan	Direct Recycling	Solar Panels [63]
R3 TECH	Hong Kong	Recycled Material Trading	Solar Panels, Frame [64]
Reclaim PV Recycling	Australia	Direct Recycling	Cell [65]
Recycle IT	Ireland	Recycling Equipment	[66]
Recycle Solar Technologies	United Kingdom	Direct Recycling	Solar Panels, Glass, Cable, Junction Box [67]
Recyklix	Slovakia	Direct Recycling	Solar Panels [68]
Reiling Glas Recycling	Germany	Direct Recycling	Solar Panels [69]
REMA PV Systém	Czech Republic	Direct Recycling	Solar Panels [70]
Rinovasol	Germany	Direct Recycling	Solar Panels [71]
RoSi Solar	France	Recycled Material Trading	[72]
SENS Foundation	Switzerland	Direct Recycling	Solar Panels [73]
SiC Processing	Germany	Recycling Equipment, Direct recycling	Slurry [74]
Silcontel	Israel	Direct Recycling	Ingot, Wafer, Cell, Solar Panels [75]
Silrec	United States	Direct Recycling	Ingot, Wafer [76]
Solar 2Recycle	United Kingdom	Direct Recycling	Cell, Solar Panels, Cable, Junction Box [77]
SolRecycle	Spain	Recycling Equipment, Direct recycling	Wafer, Cell, Solar Panels, Glass, Cable, Junction box [78]
SRS	United States	Direct Recycling	Ingot [79]
Suzhou Hedeying Metal	China	Direct Recycling	Ribbon [80]
Suzhou Minlai Silicon Energy Recycling	China	Recycled Material Trading	Wafer, Cell, Metallization Paste [81]
Suzhou Shangyunda	China	Direct Recycling	Ingot,Wafer,Cell, Panels, Slurry,paste [82]
Suzhou Shunhui New EnergyTechnology	China	Direct Recycling	Wafer, Cell, Solar Panels [83]
Tekovery	United States	Direct Recycling	Solar Panels [84]
The Recycling Village	Ireland	Direct Recycling	Solar Panels [85]
Trinity	Japan	Direct Recycling	Ingot, Wafer, Cell, Chemical Elements [86]
Yezon-PV	China	Recycling Equipment	Slurry [87]
Yuepeng New Energy	China	Direct Recycling	Wafer, Cell, Solar Panels, Slurry, paste [88]

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