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An overview of photovoltaic module's end-of-life material recycling pathways

Pregled reciklažnih putanja materijala na kraju životnog veka fotonaponskog modula

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Abstract: With rapid increase in production and installation of photovoltaic systems, recycling of photovoltaic modules is becoming more and more important. Given the recently adopted legislation in Serbia that recognises the status of prosumer, it is expected that this technology will proliferate in Serbia as well. In such a scenario, photovoltaic module recycling shall become an important issue. This paper gives an overview of technological photovoltaic recycling processes such as physical separation, thermal and chemical treatment. For each type of process, proven technologies are presented and their advantages and drawbacks are described. The results show that recycling technologies for photovoltaic industrial waste and end-of-life modules are well researched and some are already commercially available, although challenges remain in process efficiency, process complexity reduction, energy requirements and chemical use. The economic viability of photovoltaic waste remains unattainable and incentive policies are still needed to encourage manufacturers to take responsibility. In addition, it is necessary to introduce additional incentives for photovoltaic waste recyclers in Serbia until a constant inflow is established.

Keywords: photovoltaic module, PV waste, close-loop life cycle, recycling, solar potential of Serbia.

Sažetak: Sa brzim rastom proizvodnje i ugradnje fotonaponskih sistema, reciklaža fotonaponskih (PV) modula postaje sve važnija. S obzirom na skoro usvojenu zakonsku regulativu u Srbiji koja sada prepoznaje status proizvođača-potrošača, očekuje se da će ova tehnologija proliferisati i u Srbiji. U takvom scenariju, reciklaža foto-naponskih modula će postati važno pitanje. Ovaj rad daje pregled tehnoloških procesa PV reciklaže kao što su fizičko odvajanje, termalni i hemijski tretman. Za svaki tip procesa predstavljene su proverene tehnologije i opisane su njihove prednosti i nedostaci. Rezultati pokazuju da su tehnologije reciklaže za fotonaponski proizvodni otpad i module na kraju životnog veka dobro istraženi i da su neke već komercijalno dostupne, iako i dalje ostaju izazovi u efikasnosti procesa, smanjenju složenosti procesa, energetskim zahtevima i upotrebi hemikalija. Ekonomska održivost reciklaže fotonaponskih modula i dalje nije postignuta i još uvek potrebne podsticajne politike radi ohrabrivanja proizvođača za preuzimanje odgovornosti. Pored toga, u Srbiji je neophodno uvesti dodatne podsticaje za reciklere fotonaponskog otpada sve dok se ne uspostavi njegov konstantan priliv.

Ključne reči: fotonaponski moduli, PV otpad, zatvoreni životni ciklus, reciklaža, solarni potencijal Srbije, otpad.

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INTRODUCTION

Production of relatively clean energy from renewable sources is an imperative of the energy sector due to the climate crisis, the significant environment deterioration by fossil fuel burning, and perhaps the most importantly, recent global energy crisis due to the sanctions against Russian Federation. The photovoltaic (PV) technology emerged as one of the cleanest and most promising technologies for electricity generation. Solar energy is converted directly into electricity without emitting greenhouse gases during the operating life of the solar power plant. Although this technology is still undergoing a transition to a new generation of efficient, low-cost products based on thin films of photoactive materials, the volume of PV panels is rising sharply. It is expected that the total quantity of PV panels EOL will reach 9.57 million tonnes by (Chowdhury et al., 2020). More than a decade ago, in 2011, almost 70 GW was installed, which with pre-installed capacities made the overall potential of 85 TWh of electricity per year (Tao, Yu, 2015). The growth rate of PV during 2011 reached almost 70%, while in 2019 peaked another 22%, reaching to 720 TWh. This is an outstanding level of increase among all renewable technologies. With this increase, the solar PV share in global electricity generation is now almost 3%. At the same time, the price of solar electricity dropped around 89% in the past decade (OurWorldInData, 2020). However, one of the issues with PV systems is in decommissioning of PV modules at the end-of-life. Inadequate disposal of PV waste represents an environmental issue that has to be approached with due care (Sinha, 2017). Modules are expected to last about 30 years after which have to be decommissioned and disposed or re-used in some way. A concern exists about disposing them in municipal landfills as they may contain regulated materials such as, e.g., Cd, Pb and Se 2050 (Charfi et al., 2018). If they were characterised as hazardous, then special requirements for material handling, disposal, record keeping and reporting would escalate the cost of module decommissioning.

State of the art in Serbia

In Serbia however, in 2020, according to the most recent official bulletin of the Statistical Office of the Republic of Serbia, "Energy balances for 2020", the total final electrical energy consumption amounted 27880,615 GWh from which only 0,0476 % (13,261 GWh) of electricity was generated by PV systems (Statistical Office of the Republic of Serbia, 2021). Based on the data, it is clear that PV technology in Serbia is still in its infancy. Nevertheless, Serbia has a significant solar potential (Fig. 1). Based on studies from 2011, the solar irradiation in Serbia ranges from the average of 1.1-1.7 (kWh · m^{-2}) / day during January to 5.9 - 6.6 (kWh · m^{-2}) / day during July (Lamibić et al., 2011) on a horizontal plane, which provides a significant base for the PV power production. Based on the estimations by authors Milićević et al. (2012), and Stamenković et al. (2017), the total irradiation on a horizontal plane of around 1200 (kWh · m^{-2}) / year can be expected for the northwest region, and around 1550 (kWh · m^{-2}) / year can be expected for the southern regions.

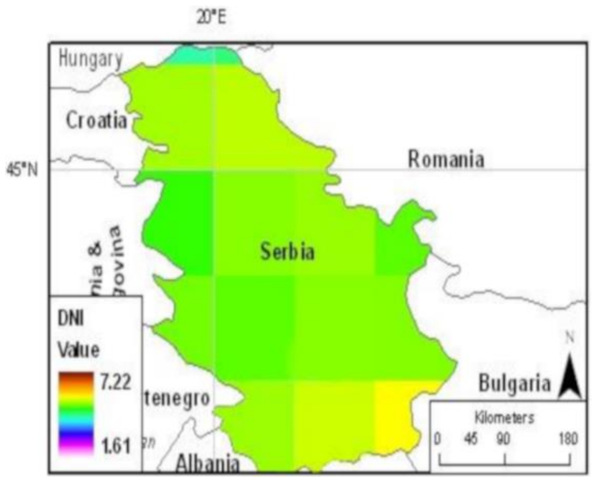

Figure 1: solar direct normal insolation in Serbia (Stamenković et al., 2017)

Given the significant solar potential of Serbia, the global energy crisis, and a significant decline in the price of PV technology, it is expected that in the forthcoming period, this technology will proliferate in Serbia as well. Another argument in favour of this is the recent legislation passed by the Government of the Republic of Serbia in 2021 in the form of the Law on the Use of Renewable Energy Sources (in Serbian) and the Decree on the criteria, conditions and manner of calculation of receivables and liabilities between the buyer-producer (prosumer) and the supplier (in Serbian). These regulations are intended to facilitate obtaining all necessary permits and make obtaining prosumer status a very simple procedure. This should be well regarded since PV technology has definite environmental advantages over competing electricity generation technologies, and the PV industry follows a pro-active life-cycle approach to prevent future environmental damage and to sustain these advantages. Still, without the adequate systemic preparation for the product end-of-life, a country should not rush toward renewables (Latinović, Tomašević, 2022), which makes this topic of high relevance to Serbia.

1. CURRENT RECYCLING INFRASTRUCTURE

Recycling is based on market forces, involving thousands of companies and municipalities worldwide. However, even one of the most valuable and easily recyclable products, such as aluminium can, is currently being recycled at a rate of only 65% in USA e.g. In Serbia this, number is far lower due to unregulated and poorly developed waste management (Garaplija, 2020). Recycling itself involves a complex matrix of operational and material specific systems, which include collection, drop-off and buy-back centres, commercial recycling centres, and material recovery facilities. Recycling of solar panels is even more complicated, because of the decades-long intervals between installing and discarding modules, and low concentration of valuable materials. Finally, they are highly geographically dispersed which represent a specific logistical problem (Latinović, Jovanović, 2018). In the following, the experience from recycling similar products in other industries is discussed and then a feasible recycling plan for solar cells is formulated.

1.1. Overview of the Global Large-Scale PV Installations

There are various types of solar PV cells on the market. The c-Si solar cell dominates 80% of the market globally (Mahmoudi et al., 2019). Thin film solar cells are second generation, semiconductor-controlled solar cells made from materials such as cadmium telluride (CdTe), and copper indium gallium (di) selenide (CIGS). However, the market share of c-Si PV panels has been projected to decrease from 92% to 44.8% between 2014 and 2030 (Chowdhury et al., 2020). The third-generation PV panels are predicted to reach 44.1%, from a base of 1% in 2014, over the same period (Xu et al., 2018; Chowdhury et al., 2020). In 2017, the total newly installed capacity was 99.1 GW globally, which was approximately the same as the total installed capacity up until the end of 2012 (100.9 GW) (Masson et al., 2018). By the end of 2017, the total installed capacity exceeded 400 GW, with the capacity in 2015-2016 rising from around 200 GW - 300 GW (Masson et al., 2018). The cumulative installed solar power capacity increased by 32% between 2016 and 2017 from 206.5 GW to 404.5 GW, as shown in Fig. 2. In 2007, Germany was the first country to sanction the commercial connection of solar power to their national grid commencing a tariff scheme. At that time, the installed global capacity was 9.2 GW (Chowdhury et al., 2020). At the end of 2017, the cumulative installed capacity increased by around 43% (Masson et al., 2018). In 2017, the Asia-Pacific region became the leading area for solar power having increased its capacity by 73.7 GW to reach a total installed capacity of 221.3 GW (Masson et al., 2018). It represented a 55% share of the global capacity. Almost one third (32.3%) of the world's solar power generation capacity was operated by China based on a substantial increase from 2016 (Oliveira et al., 2020). China for the first time became the world's largest solar power generating nation in 2017, having increased its share from around 25% in the previous year, followed by Japan and USA. In 2017, USA overtook Japan although the share of the total world capacity of both countries were reduced.

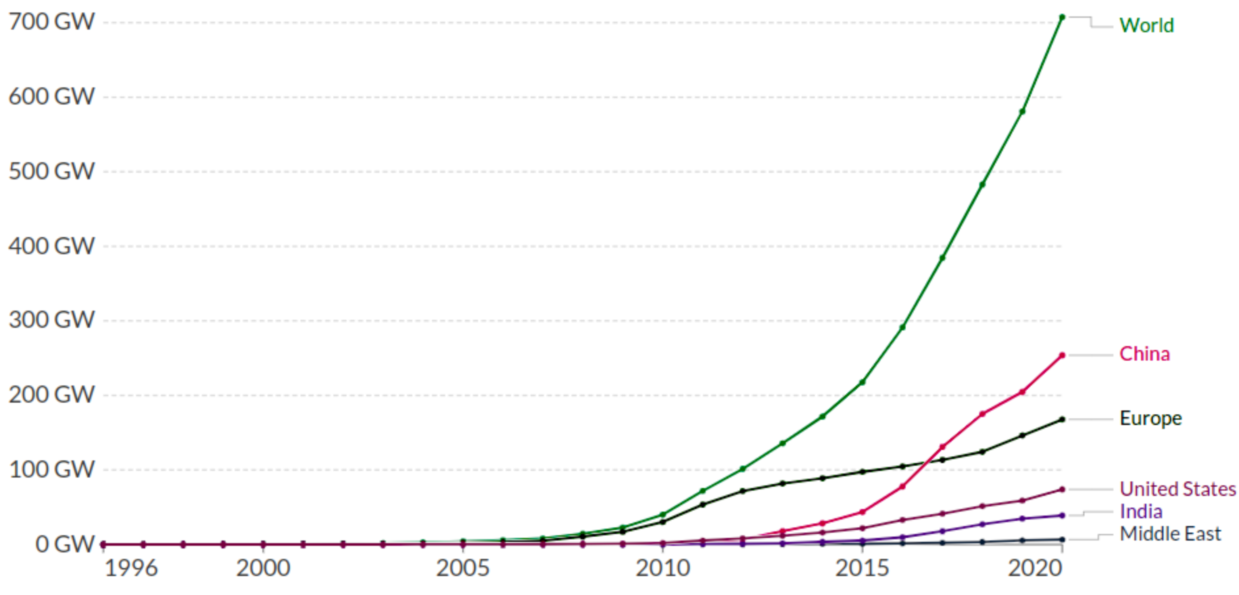

Figure 2: Cumulative installed solar capacity, measured in gigawatts (GW) (BP, 2022)

Meanwhile the European countries were the solar power pioneers and still together occupy second position in the world's capacity ranking based on a cumulative PV capacity of 114 GW, while their share has slipped to 28% (Chowdhury et al., 2020). The International Renewable Energy Agency (IRENA) estimated that at the end of 2016, there were around 250,000 metric tonnes of solar panel waste globally (Huang et al., 2017). The solar panels contain lead (Pb), cadmium (Cd) and many other harmful chemicals that could not be removed if the entire panel is cracked. In November 2016, the Environment Minister of Japan advised that Japan's production of solar panel waste per year is expected to rise from 10,000 to 800,000 tonnes by 2040 and the country has no plans to dispose of them safely and effectively. A recent statement found that the Toshiba Environmental Solutions will take approximately 19 years for reprocessing all solar massive waste of Japan produced by 2020 (Komoto et al., 2018). The yearly waste is estimated to be 70-80 times higher by the year 2034 than the year before 2020 (Komoto et al., 2018).

1.2. PV Recycling Technology

Today, couple of types of PV recycling technology are commercially available, while other technologies are under research. C-Si-based technology PV panels takes the major market share with thin film technology by using either CdTe or CIGS technology as the second largest market sector (Smith, Bogust, 2018). The recycling processes for c-Si PV panels are different from those applied to thin film PV panels because of their different module structures (Masson et al., 2018). One important distinction is that the aim of disposing of the encapsulant from the layered structure of compound PV modules is to recover the quilted glass and the substrate glass that contain the semiconductor layer (Smith, Bogust, 2018). Therefore, the purpose for recycling c-Si modules is to divide the c-Si glass and to recover the Si cells and other metals. The method incorporated in recycling Si-based PV panels is to separate the layers, which necessitates removing the encapsulant from the panel and the Si cells to recover the metals (Smith, Bogust, 2018). The removal of the encapsulant from the laminated structure is not straightforward and many possible approaches exist, including thermal, mechanical, and chemical process (Fig. 3). Chemical methods recapture metals from Si cells, for instance, by etching and other processes.

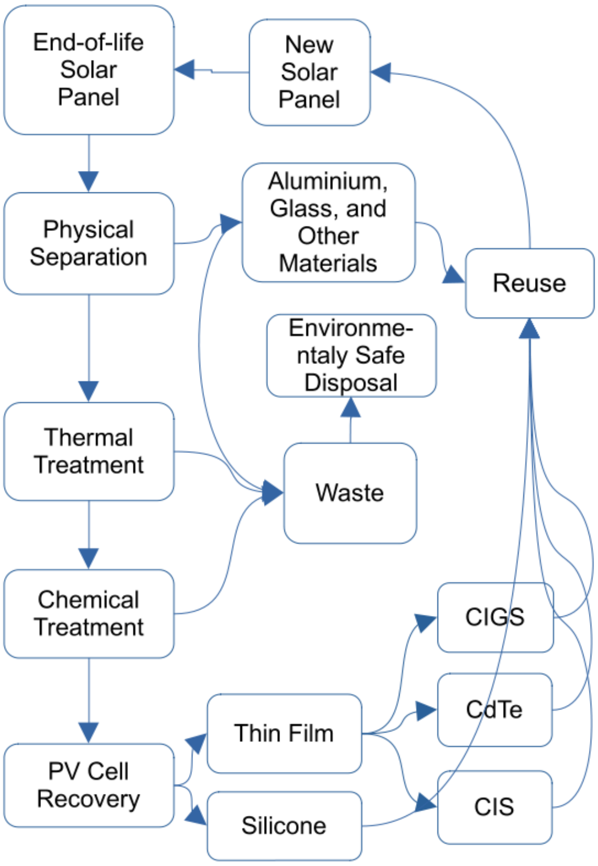

Figure 3: Solar panel recycling processes. Adapted from: (Chowdhury et al., 2018).

2. RECYCLING PROCESSES

Nowadays, most of the research and development is related to solar module recycling. Most efforts related to solar panel recycling concentrate on Si panels and aim to recover and recycle the most important parts. As stated above, there are presently three different types of recycling process applied to solar PV panels which are physical, thermal and chemical (Fig. 3).

2.1. Physical Separation

In this process, panels are primarily dismantled by removing the surrounded Al frame, as well as the junction-boxes and embedded cables (Bogust, Smith, 2020). The single part of the PV modules (panel, junction-box and cables) is shredded and crushed to inspect the individual toxicity of each part and total toxicity of the module for disposal (Smith, Bogust, 2018; Bogust, Smith, 2020). Frame is the last component to be attached to the module. It serves as a bonding component, isolates the module edges from the exterior (to avoid water infiltration, for instance) and provides a mechanical strength while keeping the overall structure light. After the frame component is separated from the module, it can be recovered through a secondary metallurgy. Other elements are also present in small quantities such as iron, zinc, silicon, cadmium and nickel, some of which are typical components of aluminium alloys (Fthenakis, 2004; Chowdhury, 2020). The replacement of elements in solar cells to repair systems is confined to replace electrical components and does not include material separation or cell treatment (Orac et al., 2015; Chowdhury, 2020).

2.2. Thermal and chemical treatment

Pagnanelli et al. used mechanical crushing in order to reduce the glass particles dimensions in order to recover different grades of the glass fraction less than 1 mm. Thermal treatment was then conducted, with an air flow of 30 litres per hour, aimed to separate glass and metal fractions. The heating rate was gradually increased until the temperature reached 650°C at a rate of 10°C/min. The reactor was then maintained at the temperature for an hour. Achieved glass recovery rate was 91% (Pagnanelli et al. 2017). Several other authors did research on different thermal treatment for recovering the polycrystalline silicon from PV (Fiandra et al., 2019). They generated high temperature by using a Lenton tubular furnace. Firstly, aluminium holding frame was dismantled in order to allow taking square samples from PV module. The process temperature in the reactor was 500°C at a heating rate of 450°C/h and the temperature was finally held for an hour (Fiandra et al., 2019). Orac et al. (2015) used thermal pre-treatment followed by acid leaching to recover copper and tin from the used circuit boards. Shin, Park, Park (2017) recycled 60 multi-crystalline Si wafers (156 mm x 156 mm) which was manufactured in South Korea by JSPV Co. Ltd. The thermal treatment was conducted in a K-Tech. Co (South Korea) furnace (1500 mm wide x 1700 mm high x 2000 mm long). The wafers were first coated with a phosphoric acid paste and then heated for 2 min at five temperatures ranging from 320°C to 400°C. The resulting recovered wafers were successfully used in manufacturing solar panels and the efficiency of the cells was found to be similar to that of the original product. Doi et al. (2001) applied various organic solvents to crystalline-silicon solar panels to remove the EVA layer, which was found to be melted by diverse types of organic solvents, of which trichloroethylene was found to be the most effective. The solar panels (125 mm x 125 mm) were treated in a process by using mechanical pressure, which was essential to suppress the swelling of EVA during soaking in trichloroethylene for 10 days at 80°C. The reclaimed Si panels could be used efficiently after the recycling process. Park, Park (2014) reported successful wet-etching processes for recycling crystalline silicon solar cells while Dattilo (2011) reported the wet-chemical extraction of metals from CIGS panels. Table 1 summarizes the currently available solar panel recycling technologies.

Table 1 - Overview of solar module recycling methods

Delamination	Material Separation	Material purification
• Physical disintegration • Thinner dissolution (Organic Chemistry) • Thermal treatment • Radiotherapy	• Erosion • Vacuum blasting • Dry and wet mechanical process • Tenside chemistry • Leaching • Etching • Flotation	• Hydrometallurgical • Pyrometallurgical

While many of these methods have been the subject of laboratory-based research, there are currently only two commercially available treatments. The US-based solar manufacturer First Solar applies both mechanical and chemical treatment methods to thin film solar panels. On the other hand, c-Si solar-panel modules have been successfully commercially recycled by a company in Germany (McDonald, Pearce, 2010).

CONCLUSION

The application of PV technology in Serbia is still in its infancy. However, due to the reduced price of this technology as well as the simplified legal procedures for obtaining prosumer status, significant proliferation of this technology is expected in Serbia as well. At the same time, the end of life of the modules that were installed among the first in Serbia is approaching. Although it is technologically possible to recycle PV waste, it is certainly a more expensive process than landfill disposal. Moreover, Serbia does not have companies capable of this type of treatment. Therefore, it is necessary to introduce adequate legislation that would impose responsibility on manufacturers and / or installers to handle the end of the life cycle of their products, while encouraging future recyclers to enter the industry. Still, at the same time, it is necessary to prepare adequate incentives for the recyclers, in order to allow for profit, that is, until a stable inflow of this waste is established, and recycling processes become even more efficient. In any case, Serbia needs to start making required steps towards PV waste recycling now because its quantity will inevitably grow sharply at some point, and then it will be too late.

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