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Fraction Separation Potential in the Recycling Process of Photovoltaic Panels at the Installation Site—A Conceptual Framework from an Economic and Ecological Safety Perspective

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Abstract: There has been a significant increase in the use of photovoltaics over the last two decades and according to many forecasts, the next two decades are expected to be characterised by even more dynamic growth. However, the long-term durability of PV panels will primarily depend on the effectiveness of legislation and processes that will be adopted to recycle an unprecedented amount of end-of-life panels to be built in the coming decades and the ones that desperately need to be recycled (predicted amount of photovoltaic waste by 2050: 78 million tonnes). As the main part of this research, a systematic review of the literature was carried out. The aim of this was to create a conceptual framework for the analysis of the fraction separation potential in the recycling process of PV panels at the installation site from the economic and environmental safety perspective, because it is agreed that the main cost that has the greatest environmental impact in the process of recycling materials from PV panels is the transport. According to this review, there is a research gap in terms of research on the recycling potential of photovoltaic panels at the site; however, those studies that touch this area clearly indicate the potential benefits, both economic and environmental.

Keywords: recycling; photovoltaic panels; management; economy; sustainable development; ecological safety

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1. Introduction

Developing and fully developed economies face a difficult challenge. On the one hand, there is the necessity to cope with the increased consumption of electricity while reducing the impact of using non-renewable resources [1]. On the other hand, balancing the environmental impact of both energy production and renewable energy production, such as recycling or utilisation of elements necessary for its production, is essential because of the aforementioned development. This development significantly accelerated urbanisation and increased the amount of consumer needs in various areas of life, at the same time leading to a drastic increase in the amount of waste from various types of human activity [2], including activities related to the production of renewable energy. For decades, energy originating from renewable resources has been considered one of the most important factors contributing to a stable future of societies, analysed on many levels, and thus a stable foundation for the absorption and diffusion of innovation in micro and macro terms (from the perspective of an organisation, region, country or group of countries strictly connected by various types of networks, such as trade agreements). What proves the interest in renewable energy is the increase in investment in renewable energy itself from USD 9.9 billion in 2010 to USD 18.6 billion in 2016 [3]. Solar energy technology is currently the third most commonly used renewable energy source in the world, after hydropower and wind farms, which are ranked first and second, respectively [4]. Solar energy is characterised by an unprecedented increase [5] in terms of the number of installations globally (both consumer and solar farms), as well as interest in new technologies that improve the efficiency of photovoltaic panels. On the other hand, an increase in the sales volume reduces the costs of designing, operating and maintaining a photovoltaic system [6–12]. Solar energy, inter alia obtained thanks to the use of photovoltaic (PV) panels, is considered to be one of the most promising markets in the field of renewable energies, and there are several key applications for it in the medium- and long-term, including small systems connected to the grid via distributed generation (often referred to as micro-photovoltaic installations) and large solar farms [13–15]. With the existing total cumulative power from photovoltaic installations amounting to about 580 GW and a staggering number of photovoltaic panels from the European perspective (4 million tons of photovoltaic panels in Europe in 2016 [16]) as well as the global one, it can be assumed with certainty that in the next 30 years renewable energy will be dominant from the global perspective [17]. Of all the solar panels installed in the world, China's share is the largest (35.3%), followed by the European Union (19%), the USA (11.8%), Japan (10.6%) and India (6%). Based on the data of 2019, it can be estimated that the globally installed PV capacity corresponds to almost two billion photovoltaic panels [18]. Photovoltaic technology is considered one of the most environmentally friendly in terms of electricity generation technologies, especially in terms of the life cycle and the method of decommissioning [17]; at the same time photovoltaic panels are responsible for much more waste per unit of energy than any source of electricity generation [19]. Unavoidably, all technologies eventually degrade to the point where they enter the phase of decommissioning (disposal or recycling), and photovoltaic panels are assumed to operate for about 25 years. This period may be shortened, subject to the influence of severe weather conditions, building fires, incentives to remove panels before the end of their life cycle, lack of maintenance, damage during transport and other factors. Although the technology of generating energy from photovoltaic panels is more environmentally friendly than conventional methods of generating energy and can achieve zero CO_2 emissions in the operation phase, waste generated during the production process and after decommissioning can significantly harm the environment and cannot be ignored, especially when analysing the forecasted quantities [20]. According to the scenario of early and regular loss, the accumulated amounts of end-of-life solar panels will reach 1.7–8 million tonnes by 2030 and 60–78 million tonnes by 2050, and in 2050, as shown in Figure 1 [21].

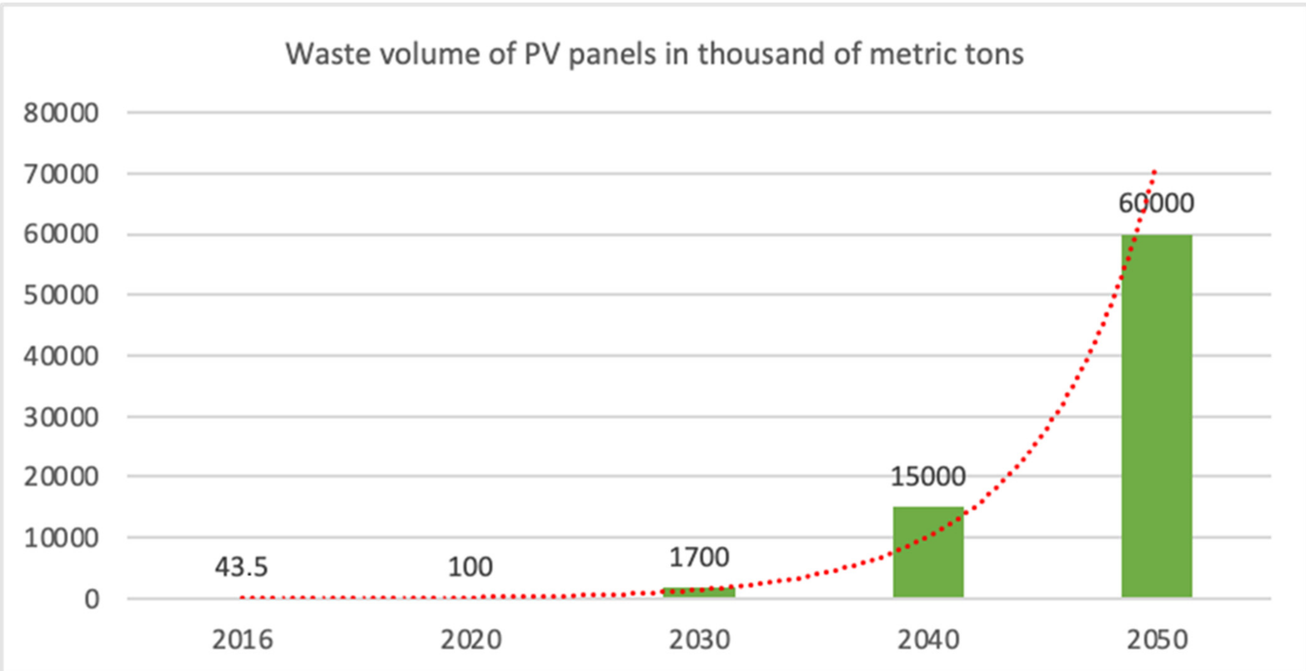

Figure 1. Estimated cumulative global waste of end-of-life solar panels [22].

The adoption of photovoltaics has grown rapidly in recent decades and is expected to continue to increase according to forecasts [22]. The next two decades are expected to be characterised by even more dynamic growth. The growth in the use of solar energy may be driven by its potential to help transition from fossil fuels to fully renewable energy sources. In order to guarantee the durability of photovoltaic panels in the long-term, it is necessary to establish efficient regulations and procedures to recycle the vast amount of panels that will reach the end of their lifecycle in the future [22]. Conscious disposal, and more importantly recycling, is crucial to avoid the loss of valuable materials used in the production of photovoltaic panels, and at the same time to prevent the spread of harmful elements, including, e.g., heavy metals (lead (Pb), tin (Sn), cadmium (Cd), silicon (Si) and copper (Cu) [22,23]) into the environment through improper disposal practices [24]. Meanwhile, in addition to preventing potential environmental degradation, recycling of photovoltaic panels can bring economic benefits in global terms. According to research by Gautam, Shankar and Vrat [25], in India alone, about 2.95 billion tons of photovoltaic waste may be generated in 2020–2047, equivalent to a value of USD 645 trillion of precious metals, and 70% of this (equivalent to USD 452 trillion) can be recovered. However, from the point of view of the recycling process as a whole, as proven by numerous analyses, the cost that has the greatest environmental impact (from 10% to even 80%) in the process of recycling materials from photovoltaic panels is the transport [26] of waste from a solar farm or a large installation to the recycling site (most often, first to the fraction separation site, and then another transport to the appropriate units recovering elements from individual fractions).

2. Materials and Methods

There are available numerous varieties of review methods used to create a conceptual framework for a given area or to systematise knowledge in a given subject, such as a critical review, a literature review, a meta-analysis, systematic search and general review [27]. These methods make it possible to reveal the landscape and the boundaries of knowledge, and to indicate what else should be known and examined [28]. As part of the research, a systematic review of the literature was carried out, the aim of which was to create a conceptual framework for the analysis of the fraction separation potential in the recycling process of photovoltaic panels at the installation site (solar farm or large solar installation) from the economic and environmental safety perspectives. The purpose of research implementing a systematic literature review is to generate structured knowledge on a given topic [29,30]. Researchers distinguish two types of systematic literature review. The first one concerns a mature research topic and proposes a conceptual framework for the synthesis of knowledge in the indicated subject. While, the second one touches upon areas that are only gaining popularity among researchers and are not yet explored, and its purpose is to create a conceptual framework for the foundations of knowledge in this field [30]. Because the studied area is an emerging topic, the research was conducted based on the second type of review. The research was performed in five stages, in line with the best practices in this area [31–40]. The first was to define the research objective, research questions and database. The second phase was to find scientific articles through the ScienceDirect® knowledge repository using the following keywords: solar panel recycling (138 articles), photovoltaic waste (807 articles), recycling location (1288 articles). No additional filters were applied at this stage (e.g., limited to a subject area). The next, third stage consisted of data extraction, i.e., capturing those articles with the indicated keywords in the title and touching the areas that will allow the achievement of the research goal. In this way, 178 articles were selected, which were then analysed for abstracts and conclusions from the research, in order to finally select articles that will be used to synthesise the results and create a conceptual framework for the research topic. The fourth and fifth stage consisted of in-depth analysis of the finally selected articles (74) that made it possible to achieve the assumed goal.

3. Results

It is estimated that there will be 60 to 78 million tonnes of photovoltaic waste by 2050, containing numerous hazardous elements, such as lead, chromium and cadmium. This will be deposited in various types of landfills or stored by various institutions, if nothing regarding this matter changes, so the recycling process will not only be more efficient in terms of material recovery, but also less harmful to the environment [41]. The global growth of interest in energy obtained through the use of photovoltaic panels has slowed down due to the shortage of resources necessary for the creation of panels, which in turn requires a proactive plan in the field of managing the withdrawal of photovoltaic modules from the market (modules with end-of-life or damaged ones) [42]. Although numerous attempts have been made all over the world to research [42] and solve the problems of electro-waste, the subject of managing the process of recycling photovoltaic panels [43] seems to be neglected from the economic and ecological safety perspectives. Moreover, insufficient information is available on the degradation modes (i.e., gradual deterioration of the properties of an element or system, which may affect its ability to operate within the acceptable limits and which is caused by operating conditions [44]) of photovoltaic modules in terms of frequency, rate of evolution and the degree of impact on the service life of the modules. Of course, a degraded photovoltaic module can still fulfil its primary function of generating electricity, even if its use is no longer optimal. However, a degraded module can be particularly problematic when the degradation itself exceeds the so-called critical threshold [45]. The research conducted on solar panels appears to prioritise the development of novel technologies at the expense of obtaining feedback on those already in use [46]. For this reason, the development of PV module recycling as a multidisciplinary research field requires an approach from the perspective of a sustainable strategy to remove obsolete or damaged panels from the market [47]. The process of recycling photovoltaic panels from a technological perspective has been described by numerous authors, and in general terms it can be presented in a consolidated manner, as shown in Figure 2.

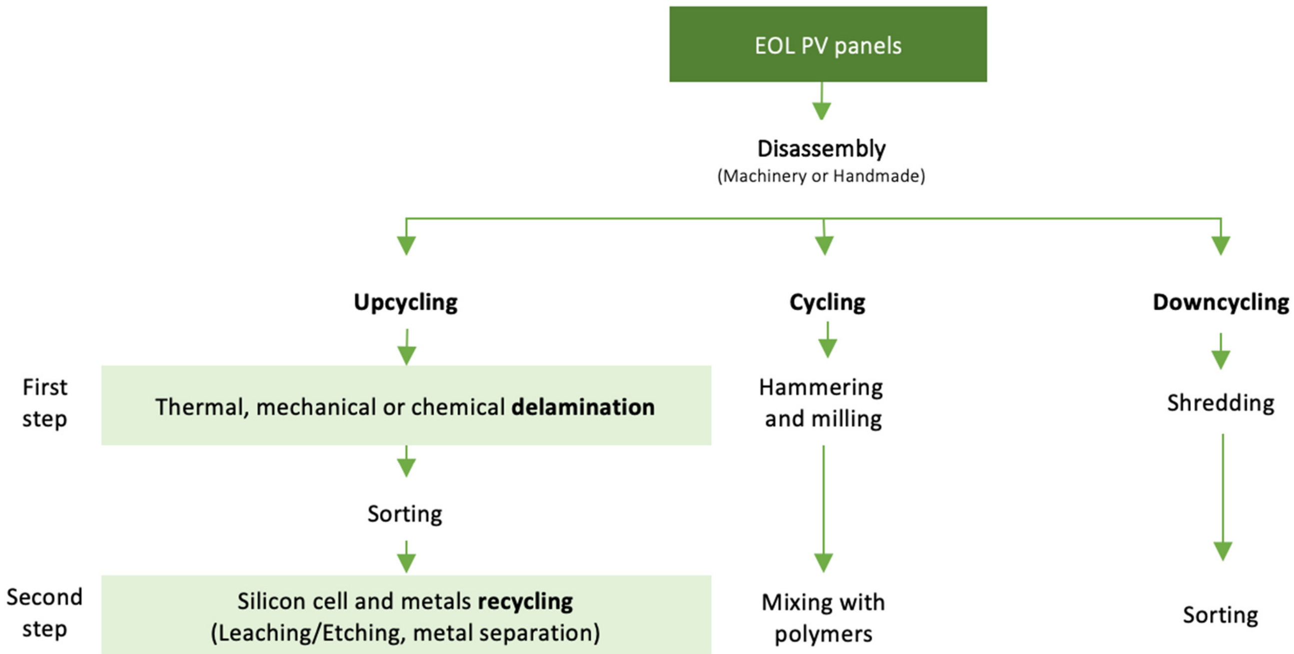

Figure 2. Visualisation of the recycling process of photovoltaic panels [48].

As indicated by numerous studies, the first stages of the recycling process of photovoltaic panels may be the most costly and resource-consuming, and have the greatest impact on the environment. After the deconstruction of photovoltaic panels at a site (a solar farm, large photovoltaic installation or even a micro-installation), they are transported to a place in which the recycling process is gaining momentum, and most often it is started there. Thus, attempts are made to separate/segregate fractions, and then transport these fractions to other places responsible for (most often) chemical treatment of individual fractions, in order to obtain the highest possible percentage of the recovery of key elements. This logic, even without a deeper multidimensional analysis, confirms the researchers' reports that out of all the types of costs, it is the transport cost as a part of the recycling process of photovoltaic panels that must be reduced for the entire process to be more profitable, both from an economic and an environmental perspective [26,49].

For this reason, due to the heterogeneous distribution of PV panel recycling centres, a solution with enormous potential for reducing the transportation costs associated with the PV panel recycling process may be the decentralisation of this process, specifically, for the initial waste treatment processes, and therefore the first stages of the entire process (e.g., fractional separation). This decentralisation, if accepted by legislation at the national and supra-regional level (e.g., European Union) could potentially be implemented by mobile units. These could carry out the process of separation of fractions while still at the location of the solar farm, after which the already separated fractions would be transported to the appropriate processing centres (recovery of key elements). This is largely characterised by the likelihood of reducing the key costs in the whole process, that is, transport costs, levelling, as it were, at least two transport links in the process (transport to the waste separation unit and transport from the separation unit to the element recovery unit, which are often different centres).

Generally speaking, recycling of solar panels is relatively complicated for two reasons; first, because the recyclable materials are in a low concentration in the panels, and second, because of the lack of logistics at the panel collection level (especially from farms) because of their geographic dispersion [50]. As already indicated, a potential solution may be offered by mobile units that start the recycling process at the location of the solar farm. It should also be noted that in recent decades the economic sustainability of photovoltaics has been the subject of numerous studies, but in the context of the cost of raw materials necessary for the production of photovoltaic panels [51–53]. On the other hand, some studies have shown that the cost of generating electricity from photovoltaic panels, taking into account the costs of recovering materials from used modules, is much lower (even by up to two-thirds while using certain recovery methods [54]) compared to a conventional fossil fuel power plant [55].

The profitability of the recycling process of photovoltaic panels is still considered low, because it is based primarily on the recovery of several materials, such as glass, aluminium or copper [56,57], and yet it can be significantly increased thanks to the recycling of silver, silicon or lead [58]. For example, researchers calculated that in Mexico alone, assuming full recovery of materials from installed photovoltaic installations, the country would obtain approximately 271 t of silver, 10 t of gold, 17 t of gallium, 10 t of indium, 139 t of cadmium and 100 t of tellurium [59]. In the United States [60] it is estimated that 69.7 GW of large PV projects could generate 9.8 tonnes (metric tonnes) of PV waste between 2030 and 2060, of which 9.2 tonnes could be recovered, equivalent to USD 22 billion. Thus, despite numerous studies pointing to the potentially complicated economic context of the recovery of materials from photovoltaic panels [61,62], the aforementioned decentralisation of the logistics process related to the collection and commencement of the recycling process still at the installation location, has the potential to change the profitability of the analysed comprehensive recycling process of photovoltaic panels. Obviously, economic sustainability largely depends on the fraction and quality of the materials that can be recovered through recycling processes. The efficacy of the proposed recycling process in satisfying the criteria of economic sustainability is largely dependent upon the worth of the materials recovered. From this point of view, one can assess the economic feasibility of the proposed recycling processes due to the modifications of the composition of PV panels, which are constantly and quickly introduced, even for the same PV technology. For example, differences in overall production techniques led, for example, to a decline in the metal content of photovoltaic panels, which ultimately resulted in a reduction in the value of the materials recovered [63–67]. A motivator for increasing the still small percentage of PV panels recycled (even at less than 10% of potential [68,69]), may be economic incentives, i.e., a method of sharing the profit from material recovery with the owner of a PV installation (a solar farm, a large area industrial installation or even a consumer micro-installation). Additionally, studies indicate that the efficiency of PV panel material recovery processes is steadily increasing (e.g., glass 59–75%; non-ferrous metals 13.5–21.8% [70]). Although consumer behaviour related to the purchase and use of photovoltaic panels has been studied by various authors, consumer attitudes toward PV disposal remain largely unexplored [71,72], indicating another research gap in sociological and economic aspects.

On the other hand, in terms of the environmental impact of the recycling process, and therefore environmental safety, there is remarkably little research available on the subject. For example, some researchers [73] only estimated the energy consumption of a standard photovoltaic module (with 125 × 125 mm multicrystalline silicon cells) compared to a module using recycled wafers. The latter resulted in a 40% reduction in the impact per kWh of electricity produced. However, the study did not provide disaggregated information on the recycling process under consideration [74]. Thus, the generation of clean and environmentally friendly electricity without depleting natural resources is the characteristic advantage of photovoltaic modules. Despite how this is a key aspect in the energy production process and the foundation of energy transition, and thus sustainable development [75], both economic and environmental costs are frequently overlooked. These are associated with the process of disposal or recycling of products that allowed this energy to be produced when they are no longer efficient and need to be replaced [76,77].

4. Conclusions

More than two decades ago, researchers emphasised the need to study the technical, economic and environmental implications (with an emphasis on the benefits) of recycling photovoltaic panels [78], especially as recycling of solar panels in the future will pose a serious threat to solid waste management, as evidenced by numerous forecasts quoted in this article. Moreover, due to the systematically growing interest in energy obtained from the sun, and thus in the technology of photovoltaic panels, which are largely made of silicon in particular, the recovery of materials from photovoltaic panels is crucial to ensure the growth stability of this type of technology. Panels using this element constitute 80% of panels worldwide [4,61], and the European Union predicts that the demand for this element only for the photovoltaic sector will increase from 33 kilotons (kt) in 2015 to 235 thousand tons in 2030 [79]. Thus, the process of recycling systematically (legally, economically, ecologically and socially) is very important.

Taking into account the economic and ecological costs of recycling photovoltaic panels in recycling centres, and the aforementioned forecasts of an increase in the number and type of photovoltaic panels that will constitute waste in the coming decades, as well as the lack of sufficient interest in the scientific community of fraction separation potential in the recycling process of photovoltaic panels at the installation site, it can be concluded that recycling at the installation site can reduce both the economic and ecological costs of the overall PV recycling process (mostly connected to transport of PV panels to recycling facilities and the related environmental costs).

5. Recommendations

After a thorough analysis of the literature on the recycling of photovoltaic panels and the potential to start this process still on site, which in turn may have significant positive economic and ecological implications, these multifaceted recommendations have been developed at a general level and their implementation may contribute to the improvement of the recycling process of photovoltaic panels.

1. The key aspect is the systematisation and unification of legislation in the field of recycling of photovoltaic panels in not so much national, but supra-regional terms. For example, numerous countries have a significant share of photovoltaics in the renewable energy basket, but most of them list PV waste as electronic waste, which is obviously an important step towards regulated end-of-life management of PV panels, but requires the separation of this type of waste from electronic waste. So far, only the European Union and the UK have developed legislation that obliges the recycling of photovoltaic panels.
2. Because of the observed potential of fraction separation from photovoltaic panels still at the site (solar farm), it is crucial to study the environmental impact of this process in detail. The potential economic and environmental benefit associated with reducing transport costs is known, but the potential environmental risks related to this activity of mobile solar panel recycling units at the site of the photovoltaic installation remains undiscovered.
3. The increase in the number of installed photovoltaic panels in global terms and the forecasts of continuing dynamic growth result in the need to raise public awareness of the lifetime of photovoltaic panels and the process of their disposal and recycling. Additionally, creating (through appropriate legislation combined with social campaigns) appropriate incentives (including especially economic ones) will prevent the storage of photovoltaic waste by solar farms, treatment centres and individual owners of photovoltaic micro-installations. This in turn may lead to their degradation and highly harmful impact on the natural environment.

The specification and implementation of the above-mentioned recommendations will allow avoiding the undesired legacy of photovoltaic waste, which will be produced exponentially in the next 10–30 years, assuming the average lifetime of the installation at the level of 25 years. Moreover, implementing the recommendations may lead to the development of more stringent aspects of the product management process, such as solar panels, and designing them with the aim of maximising the percentage of material recovery after their effectiveness.

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