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Conceptual Design of a Semi-Automatic Process Line for Recycling Photovoltaic Panels as a Way to Ecological Sustainable Production

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Abstract: The article presents the developed technology for the comprehensive recycling of depleted, used or damaged photovoltaic (PV) cells made of crystalline silicon. The developed concepts of technology and the results of research on recycling were presented on silicon photovoltaic cells and modules. The sequence of steps and the type of procedures used are proposed. A thermal delamination method for used commercial photovoltaic modules has been developed to separate the materials. In addition, a recycling line was proposed along with the selection of machines and a holistic approach to project profitability based on a SWOT analysis. The presented semi-automatic installation enables recycling on a laboratory scale. The line was designed for the assumed capacity of 30 t/h. The total energy demand for the designed line was calculated, which showed that 16.49 kWh is needed to recycle 1 ton of photovoltaic laminates. Implementation of developed solutions on an industrial scale will allow to reduce production costs, mainly thanks to energy savings, which translates into less devastation of the natural environment and reduced material consumption. In addition, the implementation of the PV module recycling system will reduce and, consequently, eliminate a significant amount of used PV devices deposited in landfills. The content of the article gives a fresh and innovative look at the essence of photovoltaic panel recycling processes in terms of production benefits as well as financial and environmental benefits.

Keywords: photovoltaic recycling; recycling technology; conceptual attitude; photovoltaic panels; recycling network planning; sustainable production; SWOT analysis; recycling policy

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1. Introduction

Photovoltaic installations are very popular because they are available to most people, and their installation does not require as much capital as in the case of installations using other renewable energy sources which is confirmed by many authors in their works [1–5]. In addition, along with the development of technology, they are becoming cheaper and more effective way to obtain electricity [6–8]. Currently, little attention is paid to the problem of recycling waste generated as a result of the development of the photovoltaic industry, but in the coming years it may turn out to be a big mistake. It is estimated that the capacity of photovoltaic installations will increase to 4500 GW by 2050. Assuming that the lifetime of the panels is 25 years, it is estimated that in 2030 solar waste will constitute up to 14% of the total generation capacity. However, in 2050 their estimated weight will be 78 million tonnes (80% of the total production capacity). In order for the use of PV installations to be ecological in the future, special attention should already be paid to the proper management of electro-waste so that it does not adversely affect the natural environment. Therefore, in the coming years, the utilization of photovoltaic modules will become a significant environmental, social and economic problem, in particular in relation to the promoted idea of sustainable production and The European Green Deal. This problem is particularly noticed in EU countries such as Poland, where PV installations have developed dynamically in recent years. Observations of the market reality indicate that at present there is no clear strategy for dealing with waste from the photovoltaic sector, there is also no information on the actual amount and type of this type of waste already transferred and deposited in national landfills. In addition, the applicable laws do not contain a separate act dealing with the rules of handling this type of waste. There is also no control of the import and use of this type of waste. Admittedly currently management of photovoltaic recycling in many countries provides for extending the obligations of producers of photovoltaic materials to their final disposal or reuse. However, further improvements in economic viability and practicality are needed. Increase the high recovery rate and the environmental performance of the PV industry with regard to the recycling of its products. The lack of legal conditions and technological solutions prompts authors to develop effective, economic and pro-ecological methods of recycling used PV modules. With these problems and challenges in mind, the authors assumed the aim of the work to prepare a conceptual design of a technological line for recycling used silicon photovoltaic panels of the 1st generation.

The presented considerations by the authors complement and extend the existing research in the field of recycling of photovoltaic panels and conceptual projects regarding semi-automatic technological lines. According to our knowledge, it is the first article in which the issues of recycling of photovoltaic panels are combined by describing the recycling technology along with the indication of appropriate machines and devices used in this process, complementing the whole considerations with a holistic SWOT analysis, while taking into account the case study—the domestic market. The key contribution of this research is to propose a conceptual design of a semi-automatic technological line for recycling photovoltaic panels of a standard size. This concept was enriched with additional determinants, ignored by other researchers regarding the profitability of launching a technological line for a given geographical destination based on the holistic SWOT analysis. In the assumption, this article presents a new look at the available literature in specific research areas such as: (I) photovoltaic recycling, (II) recycling technology, (III) sustainable management, (IV) photovoltaic decomposition and recovery devices.

The main purpose of the work was to develop a method of management (through recovery and reuse) of materials from used, damaged or exploited silicon PV cells and modules. In this context, the theses of the work were formulated according to the procedure. It is possible to recover the base material—crystalline silicon, in the process of recycling PV cells that have been damaged in the production process or come from used PV modules. Based on the silicon substrate recovered in the recycling process of PV cells, it is possible produce photovoltaic cells with electrical parameters similar to cells from primary production. The work attempts to develop its own technology for recycling silicon cells. Behind this task was carried out based on the following work schedule. Development of technology for the management of used silicon cells and modules PV. Determining the optimal parameters of the developed implementation processes recycling PV cells and modules. Proposing measurement techniques and a group of measuring instruments useful for controlling the properties of the recovered silicon substrate. Production of new PV cells based on recycled silicon wafers along with meaning of their parameters. Designing a semi-automatic installation for recycling used silicon cells PV. Conducting a preliminary analysis of economic and ecological benefits resulting from the reuse of materials recovered from damaged and worn-out PV cells and modules. Indication of prospects for further development of the proposed technology.

The article is divided into the following sections. Section 2 provides a global and national literature review on solar panel recycling technologies. Section 3 describes the research methodology that was used to design the recycling line. Section 4 contains the results of research and experiments and comments on them extensively. Section 5 presents research conclusions and prospects for further development.

2. Literature Review of the Problem

2.1. The Essence of the Research Problem

According to the report of the Polish Economic Institute on the development and potential of renewable energy in Poland [9], the amount of energy generated by photovoltaic installations in the world in 2020 was 770 TWh. In 2020, 134 TWh of solar energy was produced in the European Union countries, the most in Germany (49 TWh), Italy (26 TWh), Spain (15 TWh) and France (13 TWh). In the same year, almost 2 TWh of electricity came from photovoltaic sources in Poland. It was 1.5% of the energy produced in our country, which is a result seven times higher than in 2018. According to the data provided by [10], at the end of May 2022, 1,104,597 photovoltaic micro-installations were installed in Poland with a total installed capacity of 8.2 GW. If this dynamics of connections is maintained, it is estimated that at the end of 2022 the total installed capacity of micro-installations may reach even 10 GW. These data confirm that in 2022 Poland reached the capacity planned for 2030 by the EU (7 GW) [11]. This means that the development prospects for the photovoltaic market in Poland are favorable. The number of different sizes of solar energy installations, and thus the energy produced in them, is growing very dynamically. It is related to the growing environmental awareness of the society as well as EU and government subsidies, such as the presented program “My Electricity” [12]. An additional factor indicating the development of this part of the energy industry is the European Green Deal, one of the main assumptions of which is to decarbonise the European Union’s energy system by switching mostly to renewable energy by 2030 [13,14].

As the available literature on the subject indicates the lifetime of PV modules is 20–30 years [15,16], after this period they become waste. The amount of waste can be easily determined from the production growth chart. PV modules produced in the year 2000, for example, will become waste in 2025, and their quantity approximately it will be equal to the production volume recorded in 2000. It is estimated that the number of used modules in 2040 will be 33,500 tons [17]. Despite the dynamic development of photovoltaics, regulations regarding the recycling of photovoltaic panels in many countries have not yet been properly regulated by law. Photovoltaic waste is often treated as ordinary general or industrial waste, which is not conducive to their effective recycling, and thus the recovery of raw materials from which they are made. The exception in this regard is the Directive 2012/19/EU WEEE (Waste from Electrical and Electronic Equipment) [18], developed and introduced by the European Union in 2012. It defines solar panels as devices electronic and requires 85% efficiency in the recovery of secondary raw materials. At least 80% of this has to be used for recycling or further production. This directive contributes to sustainable production and consumption by reducing the amount of electro-waste and, moreover, by recycling and recovering this type of waste in order to reduce its quantity, use resources efficiently and recover secondary raw materials. In addition, this directive obliges producers of photovoltaic panels to organize and finance the collection and recycling of used photovoltaic modules. In practice, despite the directive introduced by the EU, some member states (including Poland) still struggle with problems resulting from the failure to develop the issue of recycling photovoltaics in national legal acts. In Poland, photovoltaics are treated as electrical and electronic waste, in accordance with the Act on waste electrical and electronic equipment of 11 September 2015 (Journal of Laws of 2019 r. item 1985). This means that their producers are obliged to manage them from the moment they become waste. The introducer, i.e., the producer, must take care of their collection and disposal [10]. According to estimates, in 2050 the global deposits of photovoltaic waste will amount to about 60–78 million tons. In the context of processing capacity reaching thousands of tons per year, these statistics may not inspire optimism. This will lead to an increase in the amount of photovoltaic waste generated. Therefore, recycling is the basic solution that effectively minimizes this problem. It is expected that reducing the negative impact of this phenomenon on the environment will become a fairly important branch of industry. That is why it is so important to properly prepare for their recycling, not only in terms of technology, but also in economic and legal terms. Therefore, it will be necessary to develop, implement and continuously develop management systems for this type of electro-waste [19]. Recycling of materials from which photovoltaic panels are made is necessary to minimize the amount of stored electro-waste, but also to ensure continuity of supplies in order to produce new installations. Many authors have addressed the problem of profitability of recycling plants in their works. The authors [20] in their work explored the circular economy strategy and business models that can enable investments in solar energy while mitigating the problem of waste. In turn, the authors [21] studied the transition from a linear economy to a circular economy and indicated the economic justification for the active involvement of companies in the development of this technology as part of respecting the climate and sustainable production. The authors in their work [22] analyzed the economic feasibility of an integrated photovoltaic (PV) system + reused BESS, which allowed to confirm the economic justification for the creation of a PV recycling installation. The authors in their work [23] conducted research in the field of environmental, economic and social dimensions of photovoltaic waste, indicated important aspects, problems and the perspective of climate protection related to PV recycling and climate protection. The conclusion from the review of this part of the literature is a valid argument for investing in recycling installations, because only they will reduce the mountain of hazardous waste, reuse it [24], save raw materials and take care of the climate.

Most of the photovoltaic panels available on the market are structures based on silicon, i.e., (mixtures of silicon and several other elements). Crystalline silicon is the material most often used for the production of photovoltaic devices that are able to convert solar radiation energy directly into electricity. The construction of PV panels is not too complicated—the basic building material is glass, which accounts for nearly 75% of the total mass of the photovoltaic module. In addition, there is an aluminum frame (approx. 10% of the mass) and a foil sealing the cells (EVA, Toddler). Interestingly, photovoltaic cells, the heart of a module, account for only 3.5% of its mass [25]. The exponential growth in the production of photovoltaic cells and modules requires the supply of more and more primary raw materials. The demand for silicon for the photovoltaic sector increases year by year, which leads to an increase in the prices of this raw material and reduces its availability on the world market. During the manufacturing processes, a significant amount of silicon waste is generated. In the era of a significant demand for silicon, the waste generated in successive production processes should be recovered and reused. With the current level of knowledge, these materials are fully recoverable and reused in accordance with the principle of sustainable production.

2.2. Literature Review of the Analyzed Problem

The issue of recycling photovoltaic cells is currently a priority topic. The first symposium devoted to the problem of using cells was organized in 1992 in the USA [26]. The first concepts of recycling waste materials and recovered from damaged, used or exploited photovoltaic modules to the production cycle appeared in the world literature at the turn of the 1990s and the 20th century. Several researchers rightly note the lack of effective methods of waste management in the PV industry.

By 2050, the waste from the photovoltaic industry will reach the mass of 78 million tons [27,28]. It will be necessary to process them, not only due to the large mass of waste, but also the significant content of component panels that can be reused. Recycling solar panels can be a big challenge. The problem here is the complexity of the materials—typical panels by weight contain about 76% glass, 10% polymer, 8% aluminum, 5% silicon, 1% copper and less than 0.1% silver and other metals. The process itself the process of recycling is multi-stage, and therefore complicated—it consists of mechanical treatment (crushing, grinding), chemical and thermal treatment. Processing is not facilitated by the fact that the panels are produced in different technologies, which often makes it necessary to adapt the recycling method to a specific product. Nevertheless, the modern level of technical knowledge allows the recovery of over 95% of the raw materials from which the panels are built [29].

The development of effective methods enabling effective management of waste generated at each stage of production allows for the recovery of secondary raw materials [30,31]. This results in ecological and economic benefits and improves the balance of raw materials and materials, enabling energy savings in relation to materials produced from virgin raw materials, and also makes it possible to cover part of the ever-increasing demand for silicon—while saving virgin raw material. Silicon is currently the most commonly used material for the production of photovoltaic devices that are able to directly convert solar energy into electricity [32]. However, the high cost of producing silicon with a purity suitable for use in the photovoltaic industry is still a problem. The increase in demand for silicon leads to an increase in the prices of this raw material and reduces its availability on the world market. In other words, basic the factor limiting the wider use of PV systems by individual consumers is the cost of PV cells and modules [33–35]. The cost of producing a 1 Wp silicon cell is primarily related to the price of the base silicon material and the outlays incurred at the stage of manufacturing the PV cells; moreover, the costs of encapsulation and assembly of modules should be taken into account here [36]. The introduction of recycling of used PV cells—through the recovery of the base material in the form of silicon wafers and their return to the production stage—can contribute to reducing material costs, which should result in lower production costs. The economic conditions of profitability of the management of secondary raw materials show that the best indicators are obtained for processes carried out on a large scale. For the recycling of silicon PV modules, this means that it should not be distributed but centralized. This entails the need to plan and organize an appropriate one infrastructure, i.e., places for collection and storage of used PV modules, and then their transport to the place where they will be processed. Depending on the technological stage at which we introduce recycling, there will be different unit operations to be used in order to recover secondary materials. Therefore, the degree of complexity of the necessary processes, their time consumption and efficiency will vary. The greatest energy savings should be expected in the case of recycling for: Broken silicon wafers on which initial technological processes were performed, waste from the crucible, processing of tops and bottoms from silicon cylinders and side scraps [37–42]. The process of silicon remelting is the most energy-intensive and the savings are the smallest here. The process of recovery of semiconductor materials or metals is the most expensive stage of recycling processes. In the technology of recycling silicon cells after silicon, silver is the most valuable material that increases the cost-effectiveness of the process. In the electrolysis process silver of high purity of 98% is obtained [43–45]. The disadvantages of this technique are: It can only be used for solutions with a high concentration of silver. Silver can also be recovered through the so-called. cementation process. It is based on an exchange reaction, where the active metal goes into solution and displaces the less active one (e.g., Ag) which goes into the solid state, which is a very economical process. Yields are of the order of 95% with a silver purity of 99.5% [46–48]. Solid-phase absorption can also be used using membranes made of conductive polymers. It is a method without the use of electricity, which allows you to reduce significant costs. The efficiency of this technique is 98%. The disadvantage is, as in the case of electrolysis, that it can only be used for high concentration solutions, over 1000 ppm. The most innovative method is the use of microbiological cells [49]. The microorganisms act as a catalyst for the redox reaction and create a current flow in the circuit. The food for the bacteria in this reaction is mainly sodium acetate. Silver recovery efficiency achieved in microbiological cells is 95–98%. The recovery of materials from modules made of indium copper gallium diselenide and cadmium telluride (CdTe) is also based mainly on electrolysis processes. In addition, during the recycling of PV modules, apart from silicon, it is possible to recover aluminum, copper, glass, as well as plastics [50]. Glass is a material that can be melted down and reused in almost 90%. The same is true for metal components, making the recycling of photovoltaic panels economically viable [51–54]. The remaining parts of the installation can be heat treated at 500 °C, thanks to which the plastic fragments evaporate. After such a process, only silicon cells that are resistant to high temperatures remain temperature. Plastic processing generates heat, which covers a significant part of the plant's heat needs. Nearly 80% of all photovoltaic cells can be reused. If they are in good working condition, they can be treated with acid and then fortified in such a way as to restore their solar radiation capturing properties [40,55–57]. Recycling of photovoltaic panels also applies to other silicon cells that can be melted down to the so-called wafers, and then create new modules from the obtained substance. In turn, the disposal of thin-film photovoltaic panels requires fragmentation of the entire element. For this purpose, a shredder capable of fragmenting 4–5 mm fractions is used [58–62]. In this way, the glass laminate holding the module breaks, making it easy to remove. In this case, too, more than 90% of the glass can be recovered for reuse. The metal in the solid form must then be separated from the metal in the mold liquid by setting them in rotation [63]. The liquid metal flows into a separate container. All other materials are cleaned and further processed [64–66].

There are not many companies that recycle photovoltaic panels. There are about 100 of them around the world. Most operate in the United States and China. Great Britain, Germany, Australia and Japan also have several. The first photovoltaic recycling plant in Europe was built in 2018 in Rousset. The project is the result of cooperation between Veolia and PV Cycle—a nationwide association that deals with the subject of photovoltaic processing. The PV Cycle facility is able to recover approximately 95% of the raw materials used to build the panels. In its first year of operation, the plant processed around 1300 tonnes of solar waste. However, it estimates that by 2022 it will have to increase its capacity to 4000 tonnes per year. If this target is achieved, it will cover around 65% of Europe's demand for electricity recycling. With these aspects in mind, the authors propose the first laboratory line for PV recycling in Poland.

According to estimates, in 2050 the global deposits of photovoltaic waste will amount to approx. 60–78 million tons. In the context of processing capacities reaching thousands of tons per year, these statistics may not be optimistic. However, it should be remembered that the recycling industry will continue to develop, which gives us a chance to avoid the flood of solar garbage. Recycling of photovoltaic panels is the only solution that will allow us to reap the benefits of solar power plants, without remorse related to the excessive use of natural resources necessary for their production.

Analyzing the literature on the subject, the authors conclude that the technology of the management process of the increasing amount of waste in the form of used PV modules (in particular with regard to the studied geographic desinitization) has not yet been fully developed and implemented on an industrial scale. Reports appearing in the form of post-conference studies contain a lot of important information about the potential possibilities of recycling PV modules. The experiments described in the literature often do not reveal specific values of the basic parameters of this process. The problem of ecological management of depleted PV modules prompts the authors to develop effective, economic and pro-ecological methods of their recycling and a friendly technology for their reuse.

3. Materials and Methods

3.1. Formulation of Design Assumptions and SWOT Analysis

Pursuant to EU Directive 2012/19/EU, for electro-waste belonging to the category of bulky waste (including photovoltaic panels), 85% efficiency is required in the recovery of secondary raw materials, of which at least 80% must be used for recycling or further production. The achievement of these values is mainly due to an effectively carried out recycling process.

Standard photovoltaic panels consist of 60 cells, which are arranged in 10 columns of 6 cells. The side length of one square link is 156 mm and the distance between them is 5 mm. The distance between the panel frame and the links is typically about 2 cm in length and about 30–50 mm in width. This gives a standard panel size of approximately 1650–1700 $\times$ 1000 mm. A dimensioned sketch of a standard photovoltaic panel for the implementation of the research problem is shown in Figure 1.

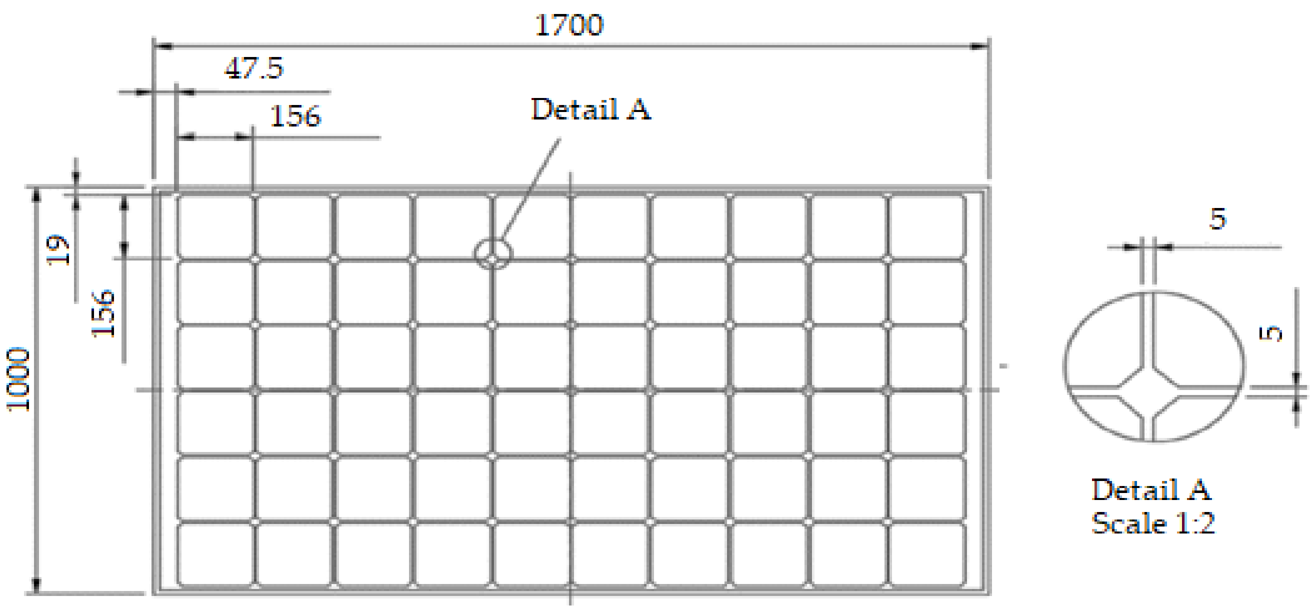

Figure 1. Sketch of a standard PV panel. Source: Own study.

The capacity of the technological line was assumed to be 30 t/h. In addition, machines for grinding panel components will be selected primarily based on the geometry of the inlet openings so that they can ensure a smooth flow of material. As the literature on the subject indicates [67,68] SWOT analysis is one of the methods of strategic analysis that allows you to assess the organization's environment, both internal and external. It allows you to make a balance of strengths and weaknesses as well as threats and opportunities related to the possibility of implementation and profitability of launching a technological line for recycling photovoltaic panels in the destination chosen for the analysis (Poland). First of all, it allows you to get to know and compare all opportunities and threats. With the help of one, well-performed analysis, we can find out the most important strengths and weaknesses of the created action plan, and thus—properly use the opportunities and avoid mistakes. SWOT analysis presented in the form consisting of The four boxes of the diagram have a holistic view of your own strategy. It helps in choosing the right path of development using its most important values. This, in turn, translates into a much safer path to success, as well as the ability to stay ahead of the competition. The SWOT analysis includes: Strengths—positive features of the analyzed research problem encouraging its support. Weaknesses—features of the analyzed problem that limit its attractiveness and potential. Opportunities—external factors favoring the development of the analyzed research problem. Threats—external factors that may adversely affect the development of the research problem. The above-described method, in the opinion of the authors, when it is not possible to present both numerical and cost data, is the most accurate approach in an attempt to assess the profitability of launching a technological line for PV recycling.

3.2. Development of a Technology for Recycling Photovoltaic Panels

The technology on the basis of which the recycling of photovoltaic panels should be performed is presented using the block diagram in Figure 2. The block diagram contains the overall process of recycling photovoltaic panels divided into processes: Mechanical, thermal, chemical and storage of the obtained materials.

The stages of the chemical process and the chemicals used in the recycling of PV panels should be carried out according to the diagram shown in Figure 3.

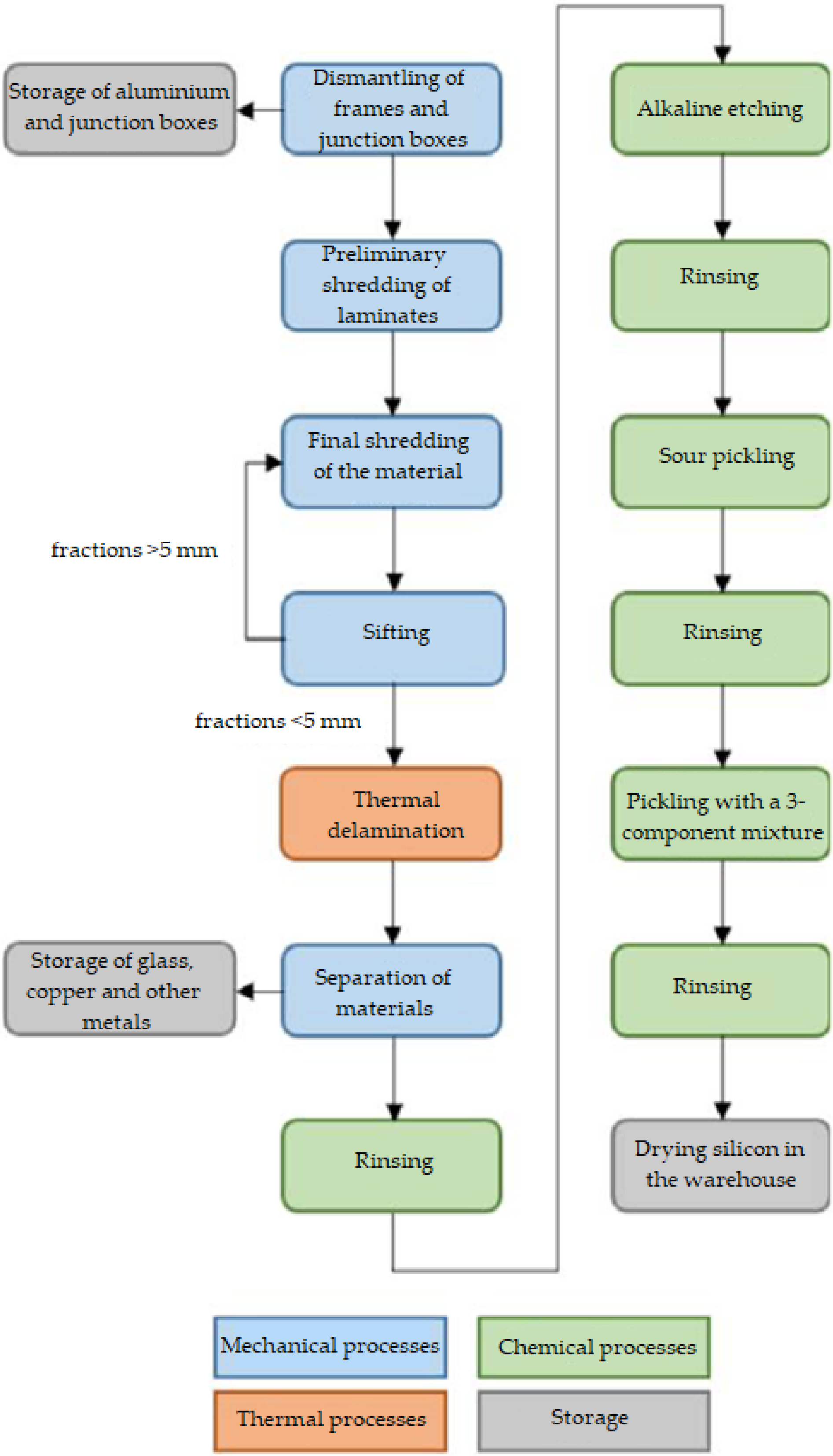

Figure 2. Block diagram of the process of recycling photovoltaic panels, taking into account the type of process. Source: Own study.

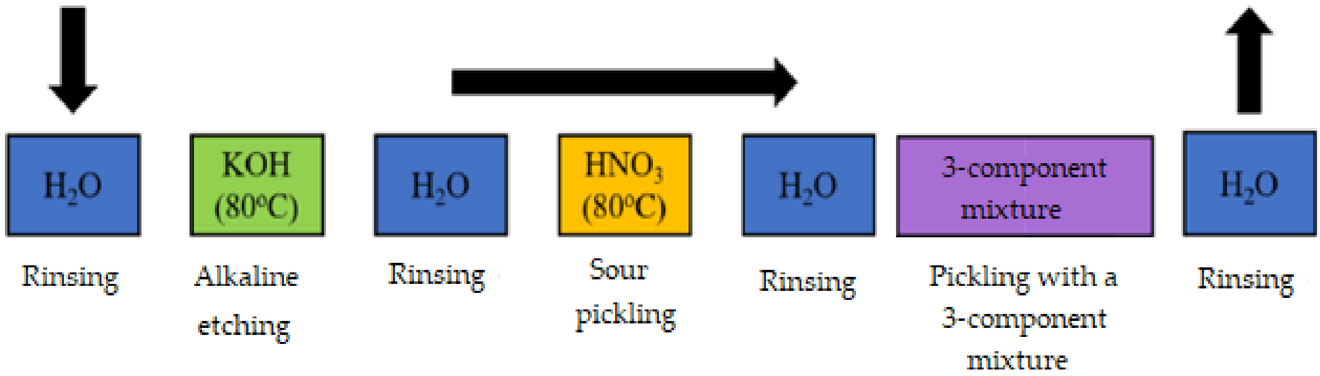

Figure 3. Stages of the chemical process. Source: Own study.

Based on the developed recycling technology, a technological line diagram was prepared, which is shown in Figure 4.

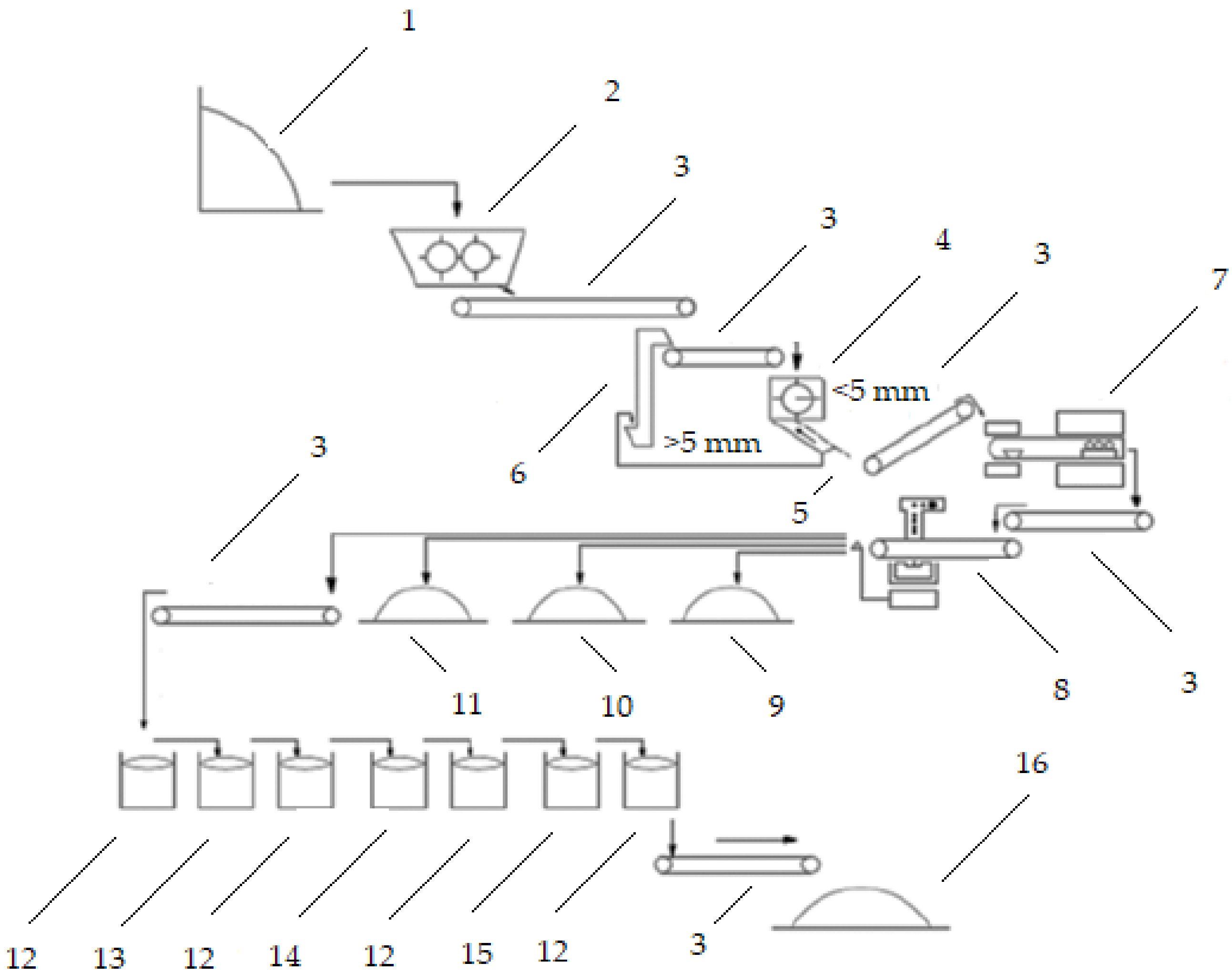

Figure 4. Diagram of a technological line for the utilization of photovoltaic panels: (1—photovoltaic cell laminate storage, 2—two-shaft shredder, 3—belt conveyor, 4—hammer crusher, 5—screen, 6—bucket conveyor, 7—furnace, 8—multisensor separator, 9—copper storage, 10—metal storage, 11—glass warehouse, 12—rinsing, 13—alkaline etching, 14—acid etching, 15—etching with a three-component mixture, 16—silicon store). Source: Own study.

The main goal of the designed semi-automatic installation will be the implementation of the chemical recycling stage. In order to implement the project of the described technological line, the following machines will be selected: Two-shaft shredder, hammer crusher, screen, multisensor separator and belt conveyors. This installation will enable the recovery of single efficient silicon wafers, and in the case of permanently damaged PV cells—the recovery of the base material (high-purity silicon). The designed installation is adapted to be used in laboratory conditions. The designed line enables automatic and controlled recovery of materials from used and damaged PV cells for several or several hundred such elements at the same time.

4. Results and Discussion

4.1. Analysis of the Energy Effects

The proper development of the PV panel recycling line requires a series of synchronized actions to strengthen the transformational potential through the use of economic, regulatory and organizational instruments as well as technological reconstruction. In order to achieve the goals supporting the implementation of PEP2040 in the field of energy transformation in Poland, it is necessary to take actions not only in the development of renewable energy, but also in technological lines for recycling their components after their end of life [69]. Based on the conducted research analyzes, a SWOT analysis (Table 1) of the profitability of launching a technological line for recycling photovoltaic panels in Poland was performed.

Table 1. SWOT analysis of the profitability of launching a technological line for recycling panels in Poland.

Type	Positive	Negative
	Strengths	Weaknesses
Inside	• the possibility of developing the line and processes after its launch, • little competition and still undeveloped industry • the ability to develop a position on the market before a significant increase in demand for the service, • caring for the environment through recycling, • generating profits from both the recycling service and the resale of recovered raw materials, • relatively low cost level and quick capital return, • increasing the country's energy security through the diversification and decentralization of energy sources.	• complicated cell recycling process, • the possibility of non-compliance with the requirements of Directive 2012/19/EU, • adapted only to panels using 1st generation cells, • possibility of high costs of transporting the panels to the plant and their storage, • lack of a dedicated unit specializing in energy efficiency, preparing and implementing support systems in this area, • lack of links and cooperation between research institutions and industry in the field of research and innovation.
	Chances	**Threats**
Outside	• large estimated increase in the amount of photovoltaic waste, • reduction in the amount of natural resources required for the production of panels (need for recycling), • the possibility of obtaining EU funding during the implementation of the line, • growing ecological awareness of the society, • stricter regulations concerning the necessity to utilize electro-waste, • increasing public awareness of environmental protection, • development and increasing the efficiency of renewable energy technologies and their recycling, • economic development of the country.	• decline in the importance of photovoltaics due to the development of other renewable energy sources, • competition in the form of large enterprises with greater know-how, • reluctance of the Polish government to comply with EU laws, • tightening up the rules on recycling panels, • lack of developed assumptions related to the construction of a recycling line in the country, • the activities of the energy lobby based on mine sources.

Source: Own study.

As strengths were identified, inter alia, little competition on the market and the generation of profits not only from the recycling service, but also from the possibility of reselling the recovered raw materials. In addition, starting early enough, it is possible to develop a position on the market even before a significant increase in demand for the service provided, which will definitely bear fruit in the future. The greatest opportunities are, among others, a large increase in the amount of electro-waste from photovoltaics and a decrease in the amount of natural resources, which necessitates paying more attention to their recovery. Among the weaknesses, particular attention should be paid to the complexity of the cell recycling process, but with the passage of time, you can expect newer and newer technologies that allow for the introduction of numerous improvements. Most of the identified threats are characterized by a low probability, but competition in the form of large companies with more capital and know-how may turn out to be quite a big problem. Despite this, on the basis of the SWOT analysis performed, it was found that the launch of a line for recycling photovoltaic panels is an innovative investment with great social, economic and environmental benefits.

4.2. Development of a Technology for Recycling Photovoltaic Panels

The process of recycling photovoltaic panels, as a relatively new technology, is a complex process that largely depends on their type. In the case of the 1st generation crystalline panels, it includes mechanical, thermal and chemical treatment of waste. The first stage (Figure 4) of machining is the dismantling of aluminum frames and junction boxes. These elements should be directed to warehouses, from which they go to industrial installations directly recycling or reselling this type of material. Then, laminates consisting of glass and photovoltaic cells laminated with EVA foil and Tedlar should be pre-shredded in the storage station (1). Successively, using an excavator, place them in a double-shaft shredder (2) for initial grinding. The material prepared in this way should be transported to the crusher via the belt conveyor (3) hammer (4), where the final grinding is carried out. The material obtained in this way should be transported by the belt conveyor (3) to the screen (5) and divided into larger fractions and smaller fractions <5 mm. Fractions larger than 5 mm should be returned to the hammer crusher (4) by means of a bucket conveyor (6) in order to crush them again. Fractions smaller than >5 mm by means of a conveyor belt (3) should be directed to the furnace (7), where the thermal delamination process should take place at a temperature of 80–90 °C. An alternative solution to thermal delamination may be to use a chemical treatment that is less favorable due to the duration of the process. However, due to the need to dispose of the used solvent, this process has a significant disadvantage, i.e., gas emission during the decomposition of the EVA copolymer [2]. For simplicity and efficiency, it is recommended to use heat treatment, which the authors believe has a greater benefit in commercial applications. After in the delamination process and leaving the furnace (7), the cleaned material should be transported by a belt conveyor (3) to a multisensor separator (8), where it should be separated into copper, metal and glass fractions. After separation, the shredded fractions should be directed to warehouses (9, 10, 11), and then to processing companies. The still contaminated silicon fraction should be directed to the chemical process by means of a conveyor belt (3) and thoroughly rinsed in ultrasonic cleaners (12). The chemical process is to make it possible to obtain pure silicon that can be reused to make cells. This process consists in removing back metallization layers (13) from the silicon fraction on it during the production of cells, acid etching of the front metallization layer (14) and removal of the anti-reflective coating and semiconductor junctions by etching with a three-component mixture (15). These layers should be deleted in the order in which they were listed. The first step in a chemical process to be used is rinsing the material in deionized water. This step should be repeated between each step and at the end of the entire process. To remove the back metallization made of aluminum, an alkaline etching should be performed. At this stage, use a 30% potassium hydroxide (KOH) solution heated to 80 °C. In the case of front metallization, which is usually performed with the use of silver pastes, acid etching should be performed. For this, a solution should be used for this process nitric acid (HNO_3) with a concentration of not less than 35% and not more than 40%, also at a temperature of 80 °C. Removal of the anti-reflective coating and semiconductor junctions should be carried out by etching with three-component mixtures. An alternative solution for recycling photovoltaic cells is to clean them with a laser. However, this solution, due to its low efficiency and high costs, has no justified application, especially in the case of fragmented material. The silicon obtained as a result of the chemical process should be transported by means of a belt conveyor (3) to be stored in a warehouse (16). This warehouse should have a low air humidity so that the silicon can be thoroughly dried. The raw material prepared in this way can be directed to companies involved in the production of photovoltaic cells for reuse. In this way, up to 95% of valuable materials can be recovered.

In order to implement the project of the described technological line, the authors selected the most important machines that will efficiently and economically implement the PV recycling process: A two-shaft shredder, a hammer crusher, a screen, a multisensor separator and belt conveyors. The main criteria considered when selecting a double-shaft shredder are the dimensions and geometry of the inlet opening. Due to the standard dimensions of photovoltaic panels presented in Figure 1, a machine should be selected with the following technical parameters: Electric motor power 4 × 110 kW, general dimencions 5000 mm × 6600 mm × 4800 mm, feeding opening 1900 mm × 2500 mm and weight 52,000 kg. An example of such a machine is shown in Figure 5.

Figure 5. Two-shaft shredder with the required technical parameters for PV recycling. Source: Own study.

The presented two-shaft shredder has been specially designed to work with the most difficult material. Their design and the materials of which the knives are made on the cutting rollers allow for the successful shredding of the components of photovoltaic panels. For the processing of materials in two-shaft shredders, the phenomenon of cutting and friction of the material between the edges of the plates placed on a pair of rollers working in opposite directions was used. Two sets of discs of the same width with hooks arranged around the perimeter, mounted on parallel shafts create an efficient working tool. The processed material is characterized by an irregular shape, the size of which is determined by the width of the cutting discs. The electronic operation controller prevents overfilling and overloading the machine. The control system can control the drive of cooperating feeders. In addition, the charging hopper can be equipped with minimum and maximum sensors material level, which is a great advantage of these machines.

When selecting a hammer crusher, the dimensions of the inlet opening may be reduced due to the earlier initial fragmentation of the material. Its efficiency should be the same as that of a two-shaft shredder, and the main criterion for minimizing the power it consumes. Therefore, the authors propose to select an impact hammer crusher, the diagram of which is shown in Figure 6.

Figure 6. Cross-section of the primary crusher for the version with 3 crushing plates. Source: Own study.

This machine should be characterized by the following parameters: Dimensions of the inlet opening: 500 mm × 400 mm, max. feeding of batch material with a diameter of 300 mm, inlet openings 0.01 m^3, capacity 22–45 t/h, electric motor with a power of 30–40 kW. The proposed device of this type is characterized by: High reliability, low operating costs, low maintenance costs, hydraulic adjustment of the crushing plate, high efficiency of the crushing elements, high degree of comminution, and most importantly, the crusher's performance remains unchanged despite the wear of the crushing elements.

When selecting a screen, special attention should be paid to its place in the process and the materials to which it will be applied. For the conceptual design of the PV recycling line, the authors propose a 7.5 kW resonant screen with the following parameters: 1000 mm × 4700 mm 2 items, screening limit 2–100 mm, capacity 150 t/h. A typical 3D model of a sifter is shown in Figure 7.

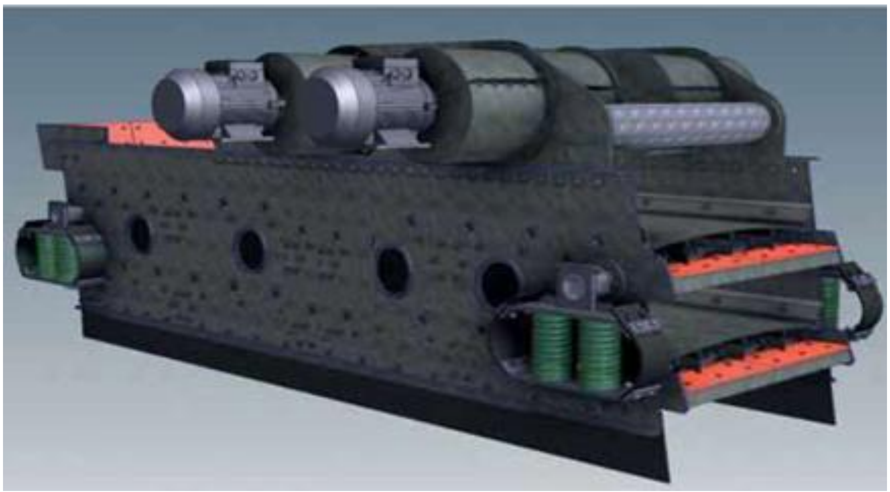

Figure 7. PC-model of the sifter. Source: Own study.

This machine is designed to screen various types of materials in the process of intermediate, recirculation and final screening in the range of 2–100 mm. The screen operates in a horizontal position, the two screen arms move in opposite direction, with rectilinear vibrations with high amplitudes, low frequency and low energy consumption. This screen has the possibility of modifying the screening arms, which will ensure proper separation of fractions and work with high efficiency.

When selecting a separator to separate the shredded and screened material into copper, metals and glass, special attention should be paid to equipping this machine with special types of sensors for their identification. So that you can perform different sorting tasks with one machine at the same time, which is a very economical solution. The machine proposed by the authors is shown schematically in Figure 8.

Figure 8. Multisensor separator. Source: Own study.

This machine, in addition to sensory metal detection and 3D and color information, also allows object-specific elemental composition to be sorted and determined by means of X-ray fluorescence (XRF) according to metal types, such as e.g., zinc, copper or brass. The low engine power of 5 kW, width 1 m and additional sensor systems are only a big advantage of these machines. In addition, the sensors used extend the possibilities for the use of secondary characteristics that can be derived from information about the shape or color. The sorting depth is thus significantly increased even with lower mass flows.

The advantages of this machine are: Increased sorting depth, increased value creation by separating metal types, solving various sorting tasks with an all-in-one machine, individual sorting programs.

Belt conveyors are responsible for transporting the material within the technological line. They are a configurable machine depending on the customer's needs. Configuration is done by adding individual modules. For cases where the machine's outlet opening is higher, use broken conveyors with adjustable inclination angle, parameters 1800 mm × 450 mm × 505 mm, height 1050–1400 mm, motor power 180 W and belt speed 3 m/min. For the transport of material between devices with the outlet opening located lower and to connect the conveyors, flat conveyors with the parameters 1500 mm × 450 mm × 505 mm should be used. An example of a broken belt conveyor is shown together with the parameters in Figure 9.

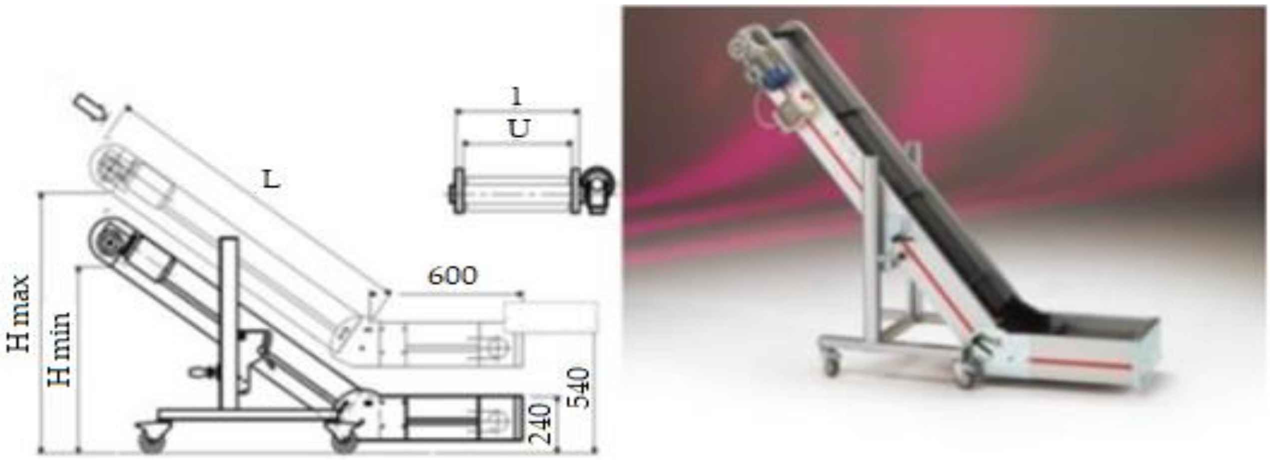

Figure 9. Example of an articulated belt conveyor. Source: Own study.

For the purposes of the design of the concept line of a semi-automatic process line for the recycling of photovoltaic panels, the total energy demand was determined, which was calculated as the quotient of the total power demand and the adopted line efficiency:

$$Total\ energy\ demand = \frac{494.66\ [\mathrm{kW}]}{30\ [\mathrm{t/h}]} = 16.49\ [\mathrm{kWh/t}] \tag{1}$$

This means that 16.49 kWh are needed to process 1 ton of photovoltaic laminates with the use of selected machines. The calculations did not take into account the energy needed to heat the furnace, as it is difficult to estimate without appropriate empirical data.

Currently, in 2022, for example in Poland, when it comes to recycling photovoltaic panels, the cost depends on the weight and amounts to approx. EUR 0.32 (net) per kilogram. For this you will have to add the cost of transport (approx. EUR 0.53 per kilometer). For example, recycling 9 370 W modules from a 3 kW PV plant will cost around EUR 64 net (excluding transport costs). In turn, for the disposal of 35 modules with a power of 360 W, from a 12 kW installation, you need to spend approx. EUR 235 net. It is worth noting, however, that sometimes the cost of recycling PV panels may already be included in their price. The presented data show that the process of utilization of photovoltaic panels in Poland is not highly cost-intensive. It should be emphasized that from the perspective of recycling, the most important determinant, apart from costs, is the weight and size of the processed photovoltaic panels. The larger it is, the greater the probability of obtaining valuable post-waste products: Regenerable PV cells, the purest metallurgical silicon and polysilicon, aluminum, copper, silver and glass, as well as rare earth metals. Even considering only the panels installed throughout the EU by 2010, 1.5 million tonnes of these raw materials are still to be recovered. Effective recycling of photovoltaic panels remains the only solution that will allow, in accordance with the protection of the environment, to use the numerous benefits of generating electricity for one's own needs.

5. Conclusions

In order to implement the project, the design assumptions were specified and the recycling technology for individual materials was developed. Among the various solutions, it was decided to use mechanical, thermal and chemical processes. Mechanical processes mainly consist of grinding and then separating the fractions of individual raw materials. The thermal process is of great importance, as it is the most effective way to delaminate photovoltaic modules. The chemical process is used to recover the most valuable raw material in photovoltaics—silicon, which is the main building block of cells. The chemical process (instead of the thermal process) and the laser treatment process (instead of the chemical process) have been presented as alternative recycling methods, but in the end the proposed recycling method was considered by the authors to be optimal in terms of time, efficiency and minimizing the negative impact on the natural environment. Based of the developed technology, a technological line was designed for the needs of which the following machines were selected: Two-shaft shredder, hammer crusher, screen, multisensor separator and belt conveyors. The line was designed for the assumed capacity of 30 t/h, but its maximum capacity, limited by the capacity of the hammer crusher, is 45 t/h. In the event of bottlenecks, it is this device that should be given special attention, as other machines have a greater possible flow of material. For the designed line, the total energy demand was calculated, which indicated that 16.49 kWh is needed to recycle 1 ton of photovoltaic laminates. These calculations only took into account the selected machines. A more precise value could be calculated taking into account the empirical data of the energy used to heat the furnace in which the module delamination process is carried out. The developed concept is characterized by the possibility of expansion depending on the needs and further development of the technology after its launch. In the second stage of the project, it may be considered to increase its efficiency by selecting additional machines. It can also be adapted to the recycling of other types of photovoltaic panels, e.g., thin film panels, which are gaining popularity. Based on the analysis, the following conclusions were drawn:

1. The dynamics of the development of the photovoltaic market in Poland is very high and it will definitely increase in the coming years. Micro and small prosumer installations constitute a large part of the market.
2. The amount of electro-waste from photovoltaics will increase significantly in the next 20–30 years. Currently, there are not many companies in the world dealing with the recycling of used PV panels, which creates a good chance for the success of the project.
3. Legal regulations concerning the disposal of photovoltaic panels are not sufficiently developed. Legal regulations should be introduced at the government level to facilitate the creation of PV recycling companies.
4. The process of recycling used photovoltaic panels is a complex and complicated process. The best results in terms of efficiency and environmental friendliness are achieved by recycling the components using mechanical, thermal and chemical processes.
5. The tests of separating PV cells from damaged and worn PV modules, and then removing subsequent layers from PV cells in order to recover a clean silicon substrate, on the basis of which it is possible to produce new cells with good parameters, performed as part of the research, have shown that recycling of PV modules is possible. As a result of the tests, it was possible to separate the cells from the PV module and remove the unwanted layers.
6. The optimal solution is to use thermal treatment to separate cells from PV modules and chemical treatment to remove metallization, contacts, ARC layer and connector p-n from PV cells. A series of tests made it possible to determine the optimal parameters of the stages of recycling silicon modules and PV cells.

7. The proposed concept of a semi-automatic installation for recycling silicon PV cells enables implementation of recycling on a semi-industrial scale. Purpose of building the presented installation has been confirmed by high parameters of PV cells, produced on a silicon substrate recovered from used PV modules.
8. Maximum efficiency of the designed technological line for recycling of PV panels is 45 t/h. To process 1 ton of photovoltaic laminates with the use of selected machines, without taking into account the energy used in thermal processes, 16.49 kWh of energy is needed. The developed concept of the line is characterized by the possibility of development and adaptation to the market requirements that may arise in the future.

Just like any other study, this one has its limitations. Further research directions in the field of recycling of used PV cells and modules cannot be limited only to silicon-based PV cells and modules. It is necessary to develop a recycling technology for photovoltaic devices made of such semiconductor materials as GaAs, CdTe, CIGS. With regard to PV modules, manufacturers tend to reduce the thickness of silicon cells. A significant decrease in the thickness of the silicon substrate in the future may make it impossible to recover them on the basis of multiple processing-recirculation. For this reason, directions and methods related to the possibility of rational management and reprocessing of silicon powders obtained from broken PV cells should be developed. It is also advisable to carry out trials to produce PV cells by sintering the recovered silicon powder. The new PV cell produced in this way may turn out to be less expensive compared to the PV cell produced from silicon powder that has undergone a remelting process. In addition, industrial scale recycling requires automation of processes in the design of a PV recycling line, which brings a number of benefits, both economic and environmental but also new areas for research and analysis, which will be undertaken and implemented in the future by the authors of the present article.

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Abbreviations

SWOT	S—strengths, W—weaknesses, O—opportunities, T—threats
WEEE	Waste from Electrical and Electronic Equipment
EVA	Ethylene-Vinyl Acetate
Toddler	Cell sealing foil
PEP2040	Poland's Energy Policy until 2040
KOH	Potassium hydroxide solution
HNO_3	Nitric acid solution
XRF	X-ray fluorescence
GaAs	Gallium arsenide
CdTe	Cadmium telluride
CIGS	Copper Indium Gallium Selenide

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