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ECONOMIC POTENTIAL OF RECOVERY AND RECYCLING OF SILICONE PHOTOVOLTAICS CELLS AND NON-FERROUS METALS AS PART OF THE TRANSITION TOWARDS A CIRCULAR ECONOMY

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ABSTRACT: The article aims to assess the economic recovery and recycling of silicon PV cells and the non-ferrous metals contained in them, taking into account the analysis of costs, benefits and factors: legal, ecological, technical, technological and social. The research methodology was based on statistical measures related to the analysis of PV structure and changes in individual years of operation. For the designated structures, the current state of knowledge and legal status in the field of recycling methods of exploited PV installations were defined. In addition, an analysis of the Polish market about selected developed countries concerning the recycling sector was performed, and the identification of key factors and barriers to the development of the analysed sector was presented. On this basis, the possibilities and directions of support for the PV recycling sector were indicated, and a SWOT analysis of possible methods of its support was made.

KEYWORDS: photovoltaic energy, solar panels, recycling, utilisation, SWOT analysis, economic dimension, circular economy

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Introduction

In the available literature, it is emphasised that the 21st century is often called the ecological century because society's awareness of ecology has increased over the last decade. However, modern economies are constantly struggling with the consequences of environmental problems such as air and water pollution, excessive waste, acid rain, the ozone hole, and the greenhouse effect, leading to dangerous climate changes. Economic management of resources is one of the solutions to the environmental problems of each of today's markets.

One of the noticeable trends in the last two decades is the process of restructuring the energy sector. Observations of market reality indicate that states, governments and local communities around the world strive to find a dynamic balance between market mechanisms and limited resources and ecological balance. The answer to this has become renewable energy sources, which, in principle, are not exhausted. These include energy from wind, water, sun, geothermal, biogas and biomass. Using them has no effect on pollution of soil, air, water and natural ecosystems (Chen et al., 2012). Due to the need to save our planet and economic crises, ecological fuels are the future of the energy sector.

Changes in the law that have been taking place in Poland in recent years and the high rates for 1 kWh of energy have made PV installations not only in households but also in public entities the most prospective source of renewable energy. Specialists are constantly looking at the situation in the photovoltaic market; forecasts indicate that the trade turnover of photovoltaics will increase and may even exceed 4,4 billion euros at the end of 2023. In 2022, previous power records were broken, and 2023 promises to be just as good. Despite this, there are new challenges arising from the disruption of supply chains and the increase in component prices, the energy crisis, and the introduction of photovoltaics into a volatile energy market.

As the number of installations increases, so does the number of outdated solar modules. Worn-out photovoltaic modules can become a dangerous source of waste that threatens the environment. The PV industry already generates waste at the production stage, but the real problem arises after the operating time, which for PV modules is optimally around 20-30 years (Kreiger et al., 2013). At the time of disassembly, waste is generated in the form of used (exploited) PV modules. The solution to the problem can be recycling and recovery of materials for reuse.

Because there is no line for recycling PV panels in Poland yet, used cells of this type are treated under Polish law as electro-waste. This approach requires changes in the law. Retired and used PV panels should be included

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in the production and recycling model related to the circular economy (Azeumo et al., 2019). This aspect had an impact on the aim of the work adopted by the authors concerning the assessment of the economic potential of recovery and recycling of silicon photovoltaic cells and the non-ferrous metals contained in them, taking into account the analysis of costs, benefits and factors: legal, ecological, technical and technological and social. The authors made a broad review of the analysed research problem in the field of:

1. The current state of knowledge in the field of recycling methods of used technical components in the field of photovoltaics.
2. Assessment of the national recycling capacity development potential.
3. Identification of barriers to market development related to recycling.
4. Identifying areas requiring public support.
5. Analysis of the risks associated with the implementation of the proposed solutions and ways to minimise them.

As presented, this article contains many important theoretical issues and practical implications. Complementing the gap in the literature on the subject related to the mentioned issues in the field of economics and the environment. The considerations in the work are presented as follows. Chapter 2 presents the material management of PV recycling and recovery from the perspective of the currently used production technology. Chapter 3 contains a description of the research methods used in response to the stated aim of the work. Chapter 4 presents the economic assessment of the recovery and recycling of PV cells and non-ferrous metals. The article ends with conclusions indicating current research limitations and future research directions.

An overview of the literature

Materials management is increasingly based on recycled (secondary) raw materials and materials, which include metals, rubber, wood, paper, and glass. Trends observed in industrialised countries indicate that the recovery of some raw materials from waste is at the level of 40-50% (Nazir et al., 2019). This is related to the increasingly developed waste sorting system and consistent national and international policies emphasising their reuse. Also, in Poland, the importance of using secondary raw materials, both from production processes and those recovered from collection points and landfills, is growing (Selvi et al., 2019). This is enforced on the one hand by the applicable and tightened environmental protection regulations and on the other – by economic reasons (Yin et al., 2014). Such activities concern, among others, steel scrap and waste, non-ferrous metals (copper, aluminium, lead, zinc and tin) and electrical and electronic waste (WEEE), batteries and accumulators, as well as recalled motor vehicles (Habisreutinger et al., 2014). It is worth

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noting that often, the recovery of secondary raw materials from waste consumes less energy than the production of the same raw material from primary sources, which also makes it pro-environmental and economically effective. Recycling of PV is of great importance in this topic (Granata et al., 2014). The elements most often used in the production of photovoltaic modules are selenium, silicon and germanium, of which silicon plays the most important role in the process. We distinguish the following technologies for the production of photovoltaic panels: crystalline, organic, thin-film, multi-layer (Tao & Yu, 2015; Marwede et al., 2013). Photovoltaic panels have a rectangular shape with dimensions of 100 × 165-170 cm, and their structure is layered. In the middle of the aluminium frame, there is a 0.2-millimetre layer of crystalline silicon wrapped in EVA foil and covered with glass (Green, 2015). Silicon is the most commonly used semiconductor in the construction of photovoltaic cells, and it accounts for about 95% of the modules currently available on the market. Large PV production technology is largely based on non-ferrous metals (Umair et al., 2019). Currently, non-ferrous metals are most often used in the PV industry: aluminium, copper, nickel, silver, and zinc. Table 1 shows the weight and value composition of a typical crystalline silicon photovoltaic module. The weight and value composition were developed by one of the key producers of photovoltaic modules in the analysis of the life cycle and its impact on the environment.

Table 1. Weight and value composition of a typical crystalline silicon photovoltaic module

Material		Libra, %
Solar cell	Silicon	4.4
	Aluminum	0.3
	Silver	0.03
Tape	Copper	0.8
	Tin	0.1
	Lead	0.01
Glass	Solar glass	67
Plastic	EVA	6.7
	PVF	0.8
	PET	2.6
	Silicon	0.9
Border	Aluminum	16

Source: authors' work based on Ostrowski (2010).

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Economic management of resources is one of the solutions to the environmental problems of the modern world. However, it requires a departure from a linear economy based on the "production-consumption-disposal" model, which will be replaced by a circular economy in which waste is the basis of various raw materials, including minerals (Kand et al., 2012). Responsible use of raw materials through recycling will contribute to savings and reduction of greenhouse gas emissions.

The basic procedure in recycling is to collect waste, process or produce it into new products, buying those products that can go through the recycling process (Fuentes et al., 2018). By contrast, recovery means any operation, the main result of which is waste serving a useful purpose by replacing other materials that would otherwise be used to fulfil a specific function or preparing waste to fulfil that function in the plant or the wider economy (D'Adamo et al., 2017). The main difference between recycling and recovery is, therefore, the end product, which is a product, material substance, or waste serving a useful purpose. Old and used photovoltaic modules can be a source of hazardous waste, even though electricity generation, with their help, brings great benefits to the world. Recycling or repurposing solar panels could release around 78 million tons of raw materials and other materials globally by 2050 (Moon & Yoo, 2017; Xu et al., 2018). If no action is taken in this direction, the problem of used PV will have a significant impact on the devastation of the environment.

When it comes to product recycling, the recycling rate and environmental performance of the photovoltaic industry are increasing. Photovoltaic technology is environmentally friendly and has become a popular way to generate energy. In Poland, the number of prosumers, i.e., owners of residential photovoltaic systems with a maximum capacity of 50 kWp, has increased rapidly, especially in the last five years (Sultan & Efzan, 2018). The number of photovoltaic parks and large industrial plants has also increased in recent years. This is mainly due to rising energy prices but also to the growing ecological awareness of society (Fiandra et al., 2019). Solar energy is safe, efficient, environmentally friendly and reliable. Therefore, photovoltaic technology holds great promise as a way to meet the world's future energy needs.

The waste from used solar panels offers an opportunity to recover valuable materials and create jobs through recycling. According to the International Renewable Energy Agency, by 2030, the total amount of raw materials that can be recovered from used modules will amount to about 404 million Euro, which is equal to the cost of raw materials that are needed to produce about 60 million new photovoltaic panels (Saliba et al., 2016). Redirection of photovoltaic panels from landfills recyclable saves landfill space and reuses the value of raw materials.

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Silicon crystal solar technology accounts for the vast majority of the solar panel market. This type of module consists of an aluminium frame, glass, copper wire, polymer layers, a back layer, silicon solar cells and a plastic junction box. The polymer layer protects the panel from the weather, but high temperatures are often needed to loosen the adhesive, which can make it difficult to recycle and dismantle the panel (Ma et al., 2019; Kenisarin, 2014). Many of these items can be recycled. Glass makes up the majority of the weight of solar panels (about 75%), and glass recycling is already a well-developed industry. Other easily recyclable materials include aluminium frames, copper wire and plastic junction boxes (Huang et al., 2017). The other materials in solar cells can be more difficult to recycle. Silver and copper are valuable ingredients, but panels usually contain very small amounts of these raw materials. Toxic metals such as lead and cadmium are also found in the photovoltaic modules. Solar panels can contain important materials such as aluminium, tin, tellurium, antimony, gallium and indium in some thin-film modules. Other solar system components include recyclable inverters, racks, and backup power systems. Inverters can be recycled in e-waste racks or similar scrap. Battery-based on-grid energy storage systems can be recycled through current battery recycling programs (Pagnanelli et al., 2017). An ideal recycling system would recover as much material as possible from the solar panel. There are many ways to recycle solar panels, and they may include some or all of the following three steps: removing frames and junction boxes; separation of glass and silicon wafers by thermal, mechanical or chemical processes; and/or separation and purification of silicon cells and special metals (e.g., silver, tin, lead, copper) by chemical processes and electric (Pandey et al., 2018). The industry is new and constantly evolving, and researchers are exploring new ways to commercialise recycling to recover most solar panel components.

It should be noted that for PV recycling to be effective, these aspects must be regulated by law (Shalini et al., 2016). As of today, the legal regulations regarding photovoltaic electro waste are defined by EU directives. Among other things, the WEEE Directive obliges all producers supplying PV modules to the European market to bear the costs of collecting and recycling PV modules in Europe (Polman et al., 2016). In developed countries, there are regulations that the manufacturer of the panels is obliged to recycle or dispose of them. However, further improvements in economy and practicality are required. Over the next few years, more and more modules will end their lives. We are still 10-15 years away from large-scale recycling (Yi et al., 2014). Nevertheless, the solar industry is already working on developing solutions for all stages of the product life cycle, from sourcing raw materials to recovery and recycling at end-of-life.

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After reviewing the literature, the authors noticed that there are no comprehensive studies on effective recycling in Poland. There are no standardised legal regulations and no PV recycling plants. In addition, there are no regulations regarding the method of storage, warehousing, and further processing. As of today, PV is treated as e-waste. Currently, it can be seen in the literature that pilot studies are being carried out on a given topic, but the results have not yet been published. Therefore, this article provides knowledge on how to properly handle PV panels after the end of their life by the principle of sustainable economic circulation.

Research methods

The main purpose of this study is to provide knowledge enabling the creation of an effective and efficient system for managing waste generated in the PV sector in Poland. Research work – literature analysis, research, interviews with experts, expert panels – were focused primarily on:

- Determining the size of the PV installation recycling market.
- Defining the possibilities (solution provider) and ways (technology) of processing waste PV cells.
- Identifying problems that need to be solved to organise an efficient PV recycling system.
- Identifying effective and, at the same time, effective ways to support the PV recycling industry so that the PV waste management system in Poland is a circular economy.

The economic assessment determined the potential revenues from PV recovery and recycling. In addition, a sensitivity analysis was used to examine the impact of certain critical variables (e.g., recyclable material price, feedstock composition, degree of purity obtained in the recycling process, volumes generated and percentage of waste collected) on specific economic indicators.

1. This study was carried out using the following research methods:
2. Data analysis based on data obtained from Eurostat.
3. Expert panels.
4. Analytical works (qualitative and quantitative analyses).
5. Analysis of the current scientific literature.
6. Case studies of selected projects implemented as part of the pilot activities on PV recycling.

Comparative methods, examining the technical advancement of recycling methods, organisation of recycling systems for RES technical components in Poland, applied financial and non-financial (organisational, legal) recycling support systems.

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In addition, the authors perform a SWOT analysis on the profitability of implementing a pilot production line for PV recycling. As the literature on the subject indicates (Glass et al., 2015; Niekurzak et al., 2023), the SWOT analysis is a tool for internal analysis of the company and its environment to optimise the company's management strategy or build a new strategic plan. The subject of the analysis can be both an organisation, a project or an investment, as well as any event in the scope of the organisation's activities. The main purpose of the analysis is to determine the current position of the examined object and its prospects and, thus, the best strategy for proceeding. Conducting a SWOT analysis forces you to think strategically, observe changes in the company's environment, and create reports and analyses that are the basis for formulating scenarios of the possible direction of the organisation's development. The accuracy of the analysis depends to a large extent on the description of the SWOT factors. As a result of the analysis, we receive 4 lists of organisation characteristics: strengths and weaknesses, opportunities (phenomena that should be developed and improved because they can become an added value for the company) and threats (events that should be avoided because they can weaken the organisation). Based on the 4 lists of scopes, deductions can be made about possible and realistic strategies for the effective implementation of the task. The SWOT analysis is the best tool to examine the degree of profitability of investing in a plant for recycling and utilisation of PV panels.

Results of the research and discussion

In Poland, due to the very small market of waste from photovoltaic panels, it is impossible to talk about the dominant method of recycling panels, including silicon modules, or several methods used because, at present, there is only one company dealing with the recycling of materials from photovoltaic panels. In this plant, silicon modules are ground and then added to a composite material used to build elements such as manholes. In other cases, in Poland, only aluminium and glass elements from a photovoltaic installation are recycled, and silicon modules are stored. The biggest problem in recycling photovoltaic panels is removing the lamination from photovoltaic modules, and this stage is the most cost-intensive due to the consumption of energy, materials and selection of the appropriate technology. The basic material for laminating photovoltaic modules is a copolymer of polyethene and polyvinyl acetate (EVA). Several delamination methods are used in the recycling process:

- The easiest way is physical removal by grinding whole modules or cutting off the laminate layer; however, the efficiency of these methods is low because the EVA film only partially separates from the glass, and it is

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difficult to isolate the semiconductor from the film residue in the next step.
- Film decomposition at high temperatures or dissolution in organic solvents is commonly used. However, they may pose a threat to the natural environment.
- The latest technique, which requires expensive equipment and is therefore not in general use, is the microemulsion technique and crushing at the temperature of liquid nitrogen (-196^{o}C).

Recycling ensures the sustainability of the supply chain in the long term, improving the recovery of materials embedded in photovoltaic modules on the one hand and, on the other hand, reducing CO_2 emissions (associated with the photovoltaic module manufacturing industry) and shortening the EPBT (Energy Pay Back Time). Moving to a more sustainable supply chain will be crucial as currently promising clean energy technologies, such as photovoltaic modules, rely on the use of materials with inherent risks in their supply (Cerchier et al., 2021). These risks include scarcity, price volatility, economic crises and other potential supply chain disruptions. Only the development of recycling and recovery, an increase in final recycling rates and the intensity of the use of waste materials will help to minimise these risks by using materials that have already been produced and are generally available. From the market point of view, energy, recycling contributes to:

- Smoothing price volatility, both for input materials and new solar modules.
- Reducing the effects of political instability.
- Increasing energy security and diversification.
- Creation of new jobs.
- Facilitating access to clean electricity and enabling full and multiple uses of production materials.
- Stop the ecological and social threat posed by the excessive amount of waste in the world, which in the future may also become a threat to human health.
- Reducing global warming and carbon footprint (recycling 1 ton of silicon photovoltaic modules can save about 800kg of CO0l).

Considering that the average lifetime of photovoltaic panels is about 25 years, there is not yet a large amount of waste from panels on the market. Currently, only panels that have been damaged or have manufacturing defects, and individual panels that were installed at the beginning of this century or were replaced due to their low efficiency compared to today, end up on the waste market. It is expected that the first solar panels will start to affect the waste market around 2034, and in larger quantities, around 432,000 in 2040, and by 2044, it will already be 2,800,000 panels. Assuming that the panel weighs on average approx. 20 kg, approx. 8,640 Mg of waste

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can be predicted in 2040, and 56,000 Mg of waste by 2044. However, the actual amount may differ from the estimated one because the panels do not completely lose their power after 25 years of use, and only it is reduced by approx. 20%, which in the case of domestic (non-commercial) installations does not have to be a prerequisite for their replacement. The photovoltaic market is a dynamically developing market. The Energy Policy of Poland until 2040 provides that photovoltaic power plants will have the largest amount of installed electricity capacity after 2035, which should amount to 11,670 MW in 2035 and 16,062 in 2040. Electricity production will increase from 2.0 TWh in 2020 to 14.8 TWh in 2040. According to the estimates of Rystad Energy, an independent energy research company, it is estimated that by 2030, materials recovered from photovoltaic panels will be worth up to USD 2.7 billion. By 2050, this value is expected to increase to EURO 73 billion. For comparison, currently, this value is only 157 million euro (Niekurzak et al., 2023). Waste recycling is characterised by a unique business model in which both waste suppliers and recipients of post-waste products are the source of revenue. According to data from the report of the International Renewable Energy Agency (IRENA) and the IEA-PVPS Program "End-of-Life Management: Solar Photovoltaic Panels", the recycling of materials from photovoltaic panels may release approximately 78 million tons of raw materials and other materials globally by 2050.

In addition, the authors noted that over the last 5 years, there has been a significant increase in the metal commodity exchange. This is a great opportunity for the development of the market for waste from photovoltaic panels. The highest drop was in 2019. Since then, metal price values have been steadily increasing. Table 2 presents a list of prices of selected metals on the exchange in 2018-2022 in USD/ unit of measure 1 ton.

Table 2. Summary of prices of selected metals on the exchange in 2018-2022

Date	Aluminum	Copper	Zinc	Lead
05.12.2017	2,054.75	6,528.00	3,111.25	2,495.00
05.12.2018	1,972.50	6,191.75	2,616.50	1,989.75
05.12.2019	1,748.25	5,893.75	2,237.75	1,906.25
04.12.2020	2,042.25	7,756.00	2,742.75	2,033.50
06.12.2021	2,596.00	9,573.50	3,170.50	2,205.25
05.12.2022	2,518.00	8,485.00	3,129.50	2,293.50

Source: authors' work based on Money.pl (2023).

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Material recovery when recycling PV modules can bring not only environmental benefits but also economic value. If solar modules are efficiently recycled, they are available again for use on the market without incurring all original production costs. It is predicted that by 2030, the total value of recycled PV materials will reach USD 450 million. For this amount, up to 60 million PV modules (with a total capacity of 18 GW) can be produced, which would be about 33% of the production in 2015. From the point of view of silicon recovery, up to 30,000 could be recovered by 2030. Tons of this material, which is equivalent to the amount of silicon needed to produce about 45 million new modules. Based on current polysilicon prices of around USD 20/kg and a recovery rate of 70% from commercial recycling processes, this is equivalent to USD 380 million. Scrapping of photovoltaic panels and other elements of the installation requires effort and costs. These costs in the current market conditions amount to approx. 2% of the purchase price of the panel, and due to the growing costs of waste management, it should be expected that they will increase. It is not profitable either from the point of view of ecology or economy.

Solar panels can be 100% recycled (Trivedi et al., 2023; Romel et al., 2023), and there is no need to store any of its components. At the moment, however, due to the small market of waste from panels, there are no companies specialising in recycling this type of waste. Parts such as aluminium frames and glass are processed in traditional metal and glass recycling plants, while the silicon modules from the panels are currently landfilled, and only a few are recycled in research facilities. However, when companies with technology enabling the recovery of silicon from these panels are established on the Polish market, they should be recycled. However, it is important to store the panels properly to prevent damage/breakage to the silicon modules, as recycling a damaged module may be more expensive than a non-damaged module.

At present, it is difficult to talk about the profitability of the Polish market recycling of photovoltaic panels because only one company does this, not recovering silicon from photovoltaic modules but grinding them and adding them to composites. According to the information obtained during the research, the recovery of silicon from photovoltaic modules can be profitable if they are made of 99.9% silicon and not contaminated with any additives. The primary acquisition of silicon for use in panels is very energy-intensive, and its recovery from used elements may turn out to be profitable. The only condition is to obtain undamaged modules for recycling with a silicon content of min. 99.9%. In the case of damaged modules and those with more impurities, it may be more profitable to grind them and add them to composite mixtures. The profitability of recycling related to the recovery of silicon will increase along with the increase in the price of silicon and technological progress enabling the optimisation of recycling processes. By 2030, approx

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8 million tons of waste from photovoltaic panels, the value of which, after processing, may amount to approximately USD 450 million and could be used to produce 65 million new PV (Savvilotidou et al., 2017). The value of waste in 2050 is already estimated at USD 15 billion, and the number of new panels that can be produced at 2 billion pieces with a total capacity of 630 GW.

One of the most important factors determining the price of the utilisation of photovoltaic panels is their weight. A similar rule applies to other types of electronic waste, and the rate is usually charged per kilogram. Average disposal prices for solar modules are around 0.50 Euro per kilogram. This price applies when the panels are delivered by the customer to the selective waste collection point. Thus, it can be easily calculated that the average weight of a 10 kW PV installation, consisting of 29 modules with a power of 340 Wp, will be about 536 kg. According to the adopted conversion rate per kilogram of material to be recycled, the cost of disposal will amount to 270 euros, which is extremely low for the price of the installation. It is also worth noting that the cost of disposal also depends on the type of material from which the panels were made. By weight, monocrystalline cells are lighter than polycrystalline modules. Thus, the cost of recycling the former will be lower. These solutions are very pro-ecological and fit into the strategy of sustainable economic circulation.

Preparing the country to manage a much larger number of new types of waste than at present and adapting the processing potential of national recycling installations (or the potential and quality of the storage base and safe transport processes) involves the need to overcome several organisational, legal, financial and technological barriers. Table 3 presents the most important barriers to the development of the PV recycling system.

Table 3. The most important barriers to the development of the PV recycling system

Barrier – name, type	Barrier characteristics	Ways to overcome the barrier
The small amount of PV recycling demand Financial and organizational barriers	The too-small size of the market results in a lack of incentives to undertake activity in the described sector. Technological solutions currently do not have much chance of commercialization. The increase in the amount of waste generated from PV in the coming years should increase the potential of the industry. However, the action will not be of a pre-emptive nature, which may result in periodic pollution of the environment due to improper storage of waste and its processing contrary to the permits held and in a way that hurts the environment.	Possible ways to overcome: • active monitoring of the amount of generated waste; • control of compliance with applicable laws; • support for the implementation of the idea of extended producer responsibility in the following areas. among others eco-design, product material card, supporting producers in creating a recycling network, e.g. by creating clusters; – collecting substrates from them for further production.

Barrier – name, type	Barrier characteristics	Ways to overcome the barrier
Penalties for improper waste management are ineffective Administrative/ financial barrier	The cost of purchasing a PV recycling line ranges from several hundred thousand to several million euro at a time. Expenditures of such magnitude will not be implemented by entrepreneurs operating on the market until PV recycling is profitable. Currently, the costs of purchase and operating activities far exceed possible revenues from the provision of services (too small market) and the sale of recyclates, semi-finished products and products.	Ways to overcome the barrier: • co-financing of development research that may be commercially applicable in the field of PV recycling; • co-financing the purchase of ready-made solutions and recycling lines; • the influence of the state on the growth of the recycling market by enforcing compliance with the applicable law in the field of proper operation of RES installations; • processing of waste by entities holding permits for the implementation of appropriate recovery processes; • increasing the effectiveness of administrative inspections of waste management in RES.
The changeability of the law Legal barrier	Entrepreneurs do not take steps to prepare for the increased amount of waste on the market, because the unstable law in Poland means a high risk for them to engage financial resources and time before the market starts to function. The experience of entrepreneurs in the industry shows that the preparations made for running a new business, even in the case of very promising markets, can be undermined by the introduction of new regulations in the short term.	Leveling method: • implement relevant legislation in advance of market developments and recycling demand.
No targeted funding for entities operating in the area of recycling Financial barrier	High installation costs and a niche in recycling (recycling processes that will not be used in other industries, e.g. for photovoltaic panels) increase the need for capital to reduce investment risk.	Possible methods of eliminating the barrier: • targeted co-financing from structural funds; • sectoral R&D programs; narrowing down the issues to those related to recycling in PV; • co-financing projects aimed at implementing a recycling line in PV.
Competition from foreign entities with PV waste processing technologies	Currently, the market is small, but prospective – probably in a few years its value will increase significantly. The opportunities related to this for the companies in the industry are leveled by the threat related to the possibility of quick entry to the Polish market of entities with the necessary waste processing technologies. This applies in particular to the recovery of raw materials from PV – processing technologies available on the market, in the event of an increase in demand for recycling in Poland, entities operating in this industry will appear globally. The barrier, which affects the sector indirectly, will probably not reduce the quantitative potential in the field of waste processing, but it will hinder the development of domestic industry enterprises and innovative technologies developed by domestic entities, thus limiting the degree of market development.	It is practically impossible to eliminate this development barrier.

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Barrier – name, type	Barrier characteristics	Ways to overcome the barrier
Too low expenditure on R&D activity Financial barrier	Expenditures on R&D activity in Poland are too low in general terms, this applies even more to the sector which is prospective from a commercial point of view but is still small in terms of value, and the chances of commercialization of solutions are small. The search for new methods of PV waste processing requires the involvement of funds in R&D activities.	Possible ways to compensate: - increase expenditures on R&D activities in PV recycling, - an increase in the allocation of EU funds to the area in question.
Possible legal regulations preferring the implementation of recycling by public entities (a reference to in-house procurement) Legal/administrative barrier	One of the barriers or factors significantly influencing the decision to operate in the sector are the applicable competition rules. Private entities may be prevented from entering the recycling market by the risk of such legal regulations which, if market activity is profitable, will result in unequal treatment of private and quasi-public entities (local government companies).	Possible countermeasures: exclusion of the possibility of implementing tasks in the field of recycling by local government units as part of their tasks.

Source: authors' work based on Szkudlarek (2019).

Directions of support for the PV recycling sector – SWOT analysis

As possible methods of supporting the development of the PV recycling sector, the authors indicate:

- subsidies from EU funds for research and development (development of innovative solutions), for the purchase of ready-made recycling solutions (implementation of innovative solutions),
- launching preferential loans and credits as well as bank guarantees for the development of PV recycling activities,
- allocating national funds to subsidise research and development and to implement innovative recycling solutions in PV,
- co-financing of scientific, research and development activities from national or EU public funds through the entity conducting scientific and research activities,
- in the case of non-repayable and refundable support, bonuses are awarded to those PV projects for which a way of recycling components after their end of life has been planned,
- tax breaks for recycling entities,
- preparation of procedures for dealing with used and damaged cells PV,
- possibly – regulating the methods of storage and transport of PV cells by law,

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- introduction of a recycling fee or similar solutions ensuring financing of recycling for RES installations,
- preparation of a national document of a strategic nature in the field of recycling in PV, containing, among others, a plan for the development of RES technical components.

Currently, it is difficult to assess the impact of potential support on the shape and size of the market (market potential). The support provided in the current financial perspective in Poland for the implementation of research and development projects consistent with the subject of this study did not bring specific business results – research and development projects in the sector of recycling photovoltaic installations are in the research or implementation (commercialisation) phase (Szkudlarek, 2019). On the European market, support, e.g., under the Life programme, is granted to individual projects; the impact of support on the development of the industry has not been examined. Projects co-financed under international EU support programs in the area of recycling in RES and electromobility have also not yet been commercially implemented. A certain threat in the case of supporting research and development in the PV recycling sector is the possibility of supporting large entities with an established position on the market, which already have their technical solutions in the area of recycling protected by patents and thus strengthening their position, reducing the level of competition on the market.

Taking into account the legal, socio-economic and ecological conditions, the authors made a SWOT analysis (Table 4) regarding the profitability of the investment in the first PV recycling and utilisation plant in Poland (Niekurzak et al., 2023).

In the above SWOT matrix, attention should be paid to the connections between the elements of its fields (so-called SWOT analysis). There is no obvious dominance of one type of connection, but it is a good sign of the fact of many mutually reinforcing links between the elements of the "Strengths" field and the elements of the field "Chances". For example, the already modern machine park increases the ability to take advantage of opportunities related to building a competitive advantage and solving staff shortages based on new technologies. The identified opportunities are also negatively associated with many weaknesses, so – well used – they give hope to overcome them. Not only that, but strengths also reduce vulnerability to some of the significant risks. Of course, there are also more pessimistic connections (such as restrictions on capital and lack of awareness of the opportunities arising from automation and Industry 4.0 solutions, which increase susceptibility to threats related to Western competition). They do not dominate the analysis as a whole but should not be downplayed.

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Table 4. SWOT analysis for the Polish PV recycling industry

Type	Positive	Negative
Inside	**Strengths**	**Weaknesses**
	• great technical potential, • well-mastered technology, • great interest from investors, • financial support, including green certificates, • no establishments with a similar profile of activity, • running a circular economy, • increase in employment, • social acceptance.	• lack of unambiguous legal regulations, • high investment costs, • complex environmental procedures, • complex disposal and recycling technology, • the possibility of recycling only 1st generation PV panels, • lack of a systemic approach to recycling issues, • limited contact between science and business, • a long period of return on investment.
Outside	**Chances**	**Threats**
	• PV is the most dynamically developing RES economy, which results in a large amount of waste obtained for processing, • technological progress, increasing efficiency and reducing the cost of installation, • increasing pressure on rational energy management and emission reduction on a European and national scale, • financial support for the implementation of pro-ecological projects by the EU, • introduction of circular economy principles aimed at limiting the extraction of primary raw materials, • development of pro-ecological technologies and their greater availability.	• external competition, especially from Asia, heavily subsidized by public funds, • lack of an effective promotion policy, • the lobby for other sources of renewable energy and fossil fuels, • lack of scientific research and cooperation between science and industry, • no guarantee of stable legal provisions.

Ecological aspects

Every industrially manufactured product, including photovoltaic panels, has an impact on the environment. In this case, the ecological analysis should cover issues such as the amount of energy needed to produce photovoltaic modules, the recycling of cells after their use and materials used or produced during their production. These factors have an impact not only on the natural environment but also on the economic analysis of using this type of electricity source. It is, therefore, reasonable to conduct a detailed life cycle assessment (LCA) analysis of photovoltaic panels and all components that are components of photovoltaic farms. This type of analysis includes the assessment of potential threats to the natural environment in the entire process of using photovoltaic cells, and its essence is to focus not only on the assessment of the final result of a given technological process. Most photovoltaic modules

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are built on a harmless basis of silicon. However, during the manufacturing process of the modules, toxic wastes arise that must be controlled with special care to prevent the degradation of the natural environment. Crystalline silicon is produced using silane gas, the production of which leads to the formation of silicon tetrachloride as a side effect. This gas can be used in a closed cycle; however, it is a toxic gas. Another chemical that can cause negative environmental effects is the very powerful greenhouse gas sulfur hexafluoride. It is used to clean the reactor used to produce silicon. Lead and small amounts of aluminium and silver are also used in the panel production process. Some manufacturers use lead-free solder. Some types of photovoltaic panels contain an extremely toxic metal – cadmium. It is used in the form of cadmium telluride (CdTe). This compound is a water-insoluble, non-metallic substance permitted for use under EU regulations. It is worth noting that one NiCd battery contains 2,500 times more cadmium than thin-film photovoltaic cells based on CdTe. For comparison, the production of 1 kWh of electricity in a traditional coal-fired power plant is 360 times higher than in the case of CdTe solar modules. However, it should be emphasised that the listed compounds do not exhaust the list of all harmful substances used in the production of photovoltaic panels, as there are various technologies for their production. One of the problems that should be taken into account in the economic analysis of the use of photovoltaic panels related to ecology is their recycling after the end of their life. Similarly, to the collection of waste electrical and electronic equipment, it is planned to oblige the producer of PV panels to possible disposal or recycling. When making analyses of the cost-effectiveness of using photovoltaic panels, it is expected that their useful life is over 30 years.

Future challenges and opportunities in Poland for PV cell recovery and recycle

Many research groups have established good recycling processes at the laboratory scale; however, the translation of such processes to the pilot scale is difficult. The upgrade will require further optimisation and research. This is possible through total quality management, where the available process can be made more effective.

Just like any other study, this one has its limitations. Further research directions in the field of recycling used PV cells and modules cannot be limited only to silicon-based PV cells and modules. It is necessary to develop recycling technology for photovoltaic devices made of such semiconductor materials as GaAs, CdTe, and CIGS. Concerning PV modules, manufacturers tend to reduce the thickness of silicon cells. A significant decrease in the

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thickness of the silicon substrate in the future may make it impossible to recover them based on 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 carryout 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 several benefits, both economic and environmental, but also new areas for interdisciplinary research and analysis.

Conclusions

In modern literature on economics and the environment, it is more and more often emphasised that photovoltaic panels are great for recycling, and most materials can be recovered for reuse, thus shortening the supply chain and having a positive impact on the environment. However, this is a process that needs time to be widely implemented and further researched to achieve its full potential for efficient recycling of all PV panel components. For this very reason, close cooperation between panel design and recycling units is necessary to ensure ever-increasing recyclability through conscious, green design. Although, in most cases, PV panels can be recycled, and thus, their negative impact on the environment is reduced, it is worth remembering that there is also a risk of improper disposal. Many institutes and researchers are working on estimating that if recycling processes were not implemented, by 2050 landfills, 60 million tons of waste from photovoltaic panels would be found. This is a huge threat to the environment and people. A lot of photovoltaic waste is transported to landfills. The release of heavy metals present in PV modules, such as lead and tin, can cause serious environmental problems. Photovoltaic panels currently also contain precious metals, such as silver and copper, the recovery of which is an opportunity for economic profit. Recycling methods for PV modules are being developed around the world to reduce the negative impact of PV waste on the environment and increase the possibility of recovering at least part of the value from used PV modules. As for the economic dimension, numerous studies indicate a potentially cost-intensive process of recycling materials from photovoltaic panels (Mahmoudi et al., 2019; Fiandra et al., 2019). The future holds the potential to change the profitability of the analysed comprehensive process of recycling photovoltaic panels. Of course, economic stability largely depends on the fraction and quality of materials that can be recovered in recycling processes. The effec-

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tiveness of the proposed recycling process in meeting the criteria of economic sustainability largely depends on the market prices of the recovered raw materials and materials (Chrzanowski & Zawada, 2023). As of today, recycling methods can only recover part of the materials, so there is a lot of room for progress in this area. Currently, Europe is the only jurisdiction with a strong and clear regulatory framework to support the recycling of solar PV.

Due to the growing interest in the subject of renewable energy sources, photovoltaic panels will become one of the most frequently used methods of obtaining clean energy. More and more research and practitioners prove that photovoltaic panels are great for recycling, and most materials can be recovered for reuse, thus shortening the supply chain and having a positive impact on the environment. However, this is a process that requires time for widespread implementation and further research. Currently, there are no known technologies to recover metals such as tellurium and indium, which are also included in photovoltaic panels. This is another challenge for scientists in their pursuit of a complete greening of the PV cell recovery process. It is worth noting that indium, due to its wide application, is considered a critical element. However, there are methods to recover silicon from photovoltaic panels, which is already an important and future element of the whole process (Han et al., 2023).

As part of future research, it is necessary to accurately identify the materials used in the production of modules, including the determination of what materials and metals were used. In addition to identifying the composition of the modules and testing their preparation for delamination, the efficiency of the mixtures used in chemical processes, emissions to the atmosphere and aspects related to the resistance of machines to the effects of the mixtures used should be examined. The results of the research will constitute guidelines for the business plan and technological line for the implementing company. Process lines within the circular economy should be fully automated by the principles of Industry 4.0.

In conclusion, the considerations presented by the authors indicate that recycling has more advantages than disadvantages and is a key step in reducing the amount of waste from installations that are supposed to bring ecological benefits. However, it should be remembered that this process requires continuous improvement and the introduction of new technologies. This will allow for an environmentally safe process of waste disposal and reduction of recycling costs and thus will have a positive impact on its economic profitability. We must prepare for the moment when the numerous currently installed photovoltaic installations will be operated in such a way that not only the energy coming from them is green, but the entire process from the moment of installing the installation to its disassembly and recycling is environmentally friendly.

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The contribution of the authors

Conception, M.N., W.L. and A.B.; literature review, M.N., W.L. and A.B.; acquisition of data, M.N., W.L. and A.B.; analysis and interpretation of data, M.N., W.L. and A.B.

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