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The assessment of solar photovoltaic in Poland: the photovoltaics potential, perspectives and development

B. Igliński[1)], G. Piechota[2)], U. Kiełkowska[1)], W. Kujawski[1)], M. B. Pietrzak[3)], M. Skrzatek[4)]

[1)] Nicolaus Copernicus University in Toruń, Faculty of Chemistry, Gagarina 7, 87-100 Toruń, Poland

[2)] GPCHEM, Laboratory of Biogas Research and Analysis, Legionów 40a/3 Street, 87-100 Toruń, Poland

[3)] Gdańsk University of Technology, Department of Statistics and Econometrics, Narutowicza 11/12 Street, 80-233 Gdańsk, Poland

[4)] Nicolaus Copernicus University in Toruń, Faculty of History, Szosa Bydgoska 44-48, 87-100 Toruń, Poland

Abstract

The following article explains the current condition of the photovoltaics sector both in Poland and worldwide. Recently a rapid development of solar energy has been observed in Poland and is estimated that the country now has about 700,000 photovoltaics prosumers. In October 2021, the total photovoltaics power in Poland amounted to nearly 5.7 GW. The calculated technical potential of photovoltaics in Poland is 153.484 PJ (42.634 TWh). This would cover 26.04% of Poland's electricity needs. The main aim of the article is to assess the level of development of the photovoltaic market in Poland, the genesis of its creation, description of the current situation and determination of the development opportunities. As part of the aim programs supporting the development of solar energy in Poland have been described and the SWOT analysis has also been performed. The strengths of photovoltaics include high social acceptance and low costs of photovoltaics system operation while opportunities include rapidly increasing technological efficiency and decreasing cost of solar systems. On the other hand, weaknesses include the high costs of photovoltaics systems and the disparities in the amount of solar energy reaching the market during the year, whereas climate change and the coronavirus pandemic are threats. In 2020, PV became an investment hit in the energy sector and an economic driver in Poland. In the difficult time of two lockdowns caused by the global pandemic, domestic PV made a significant contribution to the maintenance of investment processes in the amount of PLN 9.5 billion and provided Poland with 35 thousand jobs. In 2020, 1.5% of the country's electricity came from PV sources. In 2021, it will be 3.5%, and by 2025, solar energy will provide approx. 10% of Poland's electricity. It is worth examining the development of photovoltaics from a broad and long-term perspective. The spectacular development of photovoltaics in Poland is due to hitting the right time window and reducing technology costs, but most of all, it is based on the cooperation of stakeholders and trust in the regulatory environment.

Keywords: photovoltaics; photovoltaics in Poland; photovoltaics potential in Poland; SWOT analysis of photovoltaics

Introduction

The European Union (EU) has set individual targets for each Member State to attain the indicated percentage of energy obtained from renewable energy (RE) sources (Kies et al. 2021). For Poland, it was at least 15% by 2020 (and 32% by 2030 for the whole UE) (Veum and Bauknecht 2019). However, it is already evident that Poland – just like several other Member States – will not achieve its national target within the specified period. Although the production of energy from RE sources is gradually increasing, the Polish economy still relies on coal. However, despite the lack of realistic prospects for meeting the EU's commitment, further development of the RE sector in Poland – and particularly PV – still seems to be a foregone conclusion (Li et al. 2020).

The PV market in Poland is currently experiencing a fast development, which has been driven by such things as the amendment of the RE Act (RE Act 2015), which changed the definition of the prosumer, as well as the drop in prices of PV panels and the unification of the VAT rate, and government programs such as "My Electricity" (My Electricity 2021). The "My Electricity" program is one of Europe's largest funding programs for prosumer PV systems with a capacity of 2-10 kW. In 2020 the program's balance sheet to date was 73,000 applications and 408 MW of installed capacity and – as provided by the National Fund for Environmental Protection and Water Management – the value of investments in household-level PV made by Polish households thanks to the program has already reached about PLN 1.8 billion (1 PLN = 0.27 USD; based on 2021 PLN to USD exchange rate). Domestic RE is becoming increasingly popular in Poland since solar energy is significantly cheaper than that obtained from traditional sources. Companies that opt for PV also benefit from lower energy bills, as well as greater energy security and a more environmentally friendly image (Shafique et al. 2020).

In Polish conditions, a PV system should work effectively for at least 25-30 years (Igliński et al. 2016a). When rising energy prices – a common phenomenon in Poland in recent years – are also taken into consideration, such investment will also be beneficial for the customer, allowing them to establish energy independence.

Despite its changing weather and seasons, Poland has adequate conditions for PV systems to function relatively well. Poland's solar conditions are "optimal", as despite appearances, too much heat and sunshine can damage solar systems due to overheating (Klepacka et al. 2018).

While the COVID-19 pandemic did not stop PV development in Poland, the industry's concerns due to more than 70% of PV panels being manufactured in China proved justified. Nonetheless, despite initial problems due to production stoppages in Asia, which caused short-term delays in the transport of PV modules, there was no complete disruption of supply continuity. Some investment projects in Poland have been suspended or postponed, but their implementation is not at risk (IRE 2020).

The article aims to present PV's history, fast development in the world and Poland – its origins, current state, and prospects for development. To that end, programs supporting PV in Poland were approximated and the technical potential of PV was calculated. To examine the PV sector in Poland, a SWOT analysis was conducted as well. The summary and conclusions of the presented article are presented in the chapter "Discussion and summary".

PV energy in the world

PV provides a global energy mix, with more and more private individuals, local governments, and entrepreneurs eager to invest in it (Gordon et al. 2021). Importantly, there is less reluctance on the part of energy network operators to use PV today compared to a decade ago (Lan et al. 2021).

Dynamic development of PV is possible thanks to the constantly decreasing costs of the technology (Gonzalo et al. 2020). Between 2010 and 2020, the weighted average cost of electricity generation from PV fell worldwide by 77%, down to USD 85 per MWh. Many projects, especially in geographically conducive locations, make it possible to generate such energy at a price as low as USD 20-30 per MWh. Therefore, PV is the most popular source of new generation capacity in the electricity sector worldwide (Garlet et al. 2020).

In 2020, PV had another record year in terms of installed capacity, which amounted to 139 GW. The total capacity reached 760 GW (Fig. 1). The PV market developed best in China, the United

States, and Vietnam, but several other countries saw notable expansion (including Poland). There have been major investments in distributed rooftop PV systems (Fig. 2) (Renewable Energy Policy Network 2021; Kumar and Jayanti 2021).

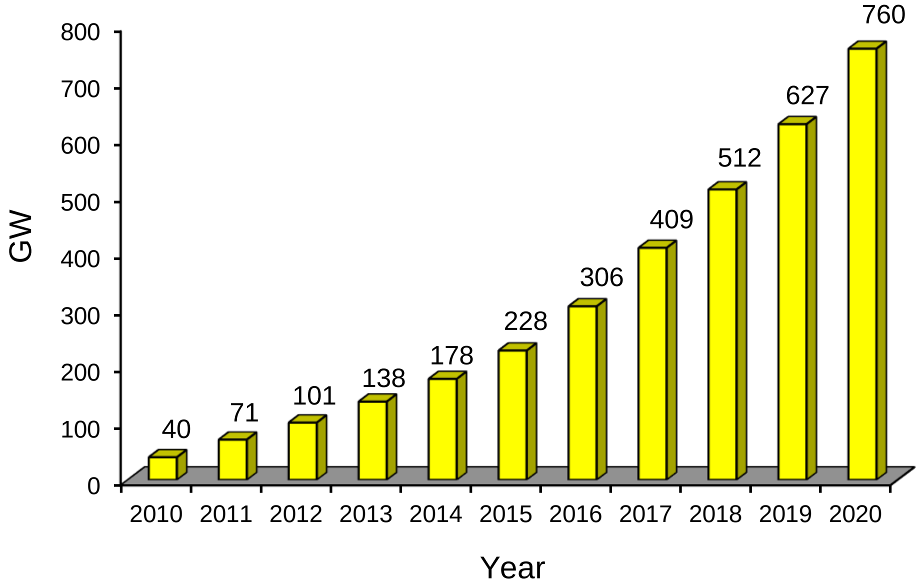

Fig. 1. Global installed PV capacity [GW] in 2010-2020 (own elaboration from (Renewable Energy Policy Network 2021))

Fig. 2. A private investor’s roof PV system, Lubień Kujawski, Poland (photo: B. Igliński)

China, the world leader in solar energy, added a total of 48.2 GW of PV capacity (15.5 GW of prosumer (distributed) PV and 32.7 GW of centralized PV) in 2020 (Li 2021). The largest PV capacity was installed in Qinghai (4.1 GW), Hebei (4.9 GW), and Guizhou (5.2 GW) provinces. By the end of the year, the total grid-connected capacity in China exceeded 253 GW (Qiu et al. 2022).

In 2020, Vietnam commissioned 11.1 GW of PV power. This is another massive increase in installation capacity, with that in previous years amounting to 8 MW in 2017, 106 MW in 2018, and 4.8 GW in 2019. So far, few large PV systems have been set up in Vietnam. In 2020, is the dominant solution selected was distributed (rooftop) PV (Renewable Energy Policy Network 2021).

Japan added 8.2 GW of new PV capacity, an increase of 16% year on year. Its total PV power amounts to 71.4 GW. The share of PV in Japan's electricity production increased from 7.4% in 2019 to 8.5% in 2020 (Renewable Energy Policy Network 2021).

The coronavirus pandemic has significantly slowed down the development of PV in the EU. Despite many problems (including with supplies), 2020 turned out to be the second-best year in history. The PV capacity increased by 15% (19.3 GW), reaching a total of over 140 GW (Renewable Energy Policy Network 2021, Wierling et al. 2021).

In many countries, the share of PV in the energy mix is gradually increasing. In Japan, it is 8.5%, in Italy 9.8%, in Chile 9.8%, in Australia 9.9%, in Greece 10.4%, in Germany 10.5% and in Honduras 11.2% (Renewable Energy Policy Network 2021). Moreover, many countries – including Poland, Spain, and the United Kingdom – broke records of PV energy production due to two factors: the increasing PV power in a given country, as well as higher energy production from PV panels thanks to cleaner air during the lockdown period (Renewable Energy Policy Network 2021).

Development of PV sector in Poland

Merely a few years ago Poland was dominated by the belief that PV technology is a solution that will only be accessible in some distant future (Gnatowska and Moryń-Kucharczyk 2021). As such, the National Renewable Energy Action Plan adopted in 2009 assumed reaching as little as 3 MW of PV energy generation by 2020 – a level that has already been exceeded by more than 1,900 times**.** As of September 30, 2013, Poland had only 14 small PV systems with a total capacity of 1.75 MW (Igliński et al. 2016a).

Despite earlier skeptical forecasts, the niche PV has become a new trend in Poland (Gnatowska and Moryń-Kucharczyk 2021), who enjoys good conditions for using solar energy. The weather conditions in Poland are similar to those in Germany (depending on the region, annual sunshine hours in Poland range from 1,390 to 1,900), and as such, nothing stands in the way of using sunlight efficiently for electricity generation (Kühnbach et al. 2020).

The years 2018-2021 brought an acceleration in the development of RE in Poland, which has been enabled by several factors: the full launch of the auction system, EU subsidies, "My Electricity" program subsidies (My Electricity 2021), as well as an increase in the price of emission allowances, which further improved RE's competitiveness. It was also a period of high wholesale electricity prices, averaging almost PLN 230 per MWh, which were among the highest in the EU (IRE 2021).

The years 2020 and 2021 belonged to solar energy. In Poland, the subsequent PV capacity levels were ahead of all previous plans for this sector's development. The installed capacity has been increasing successively, and the growth rate has been extremely high for the last two years (Rataj et al. 2021). 2020 was the best year in the history of PV development in Poland – by the year's end, the installed PV capacity amounted to 3,936 MW. Thus, according to Solar Power Europe, in 2020 Poland ranked 4th in terms of increasing installed PV capacity in the EU, with only Germany, the Netherlands, and Spain ranking higher (IRE 2021). In October 2021, Poland's PV capacity amounts to nearly 5.7 GW (Fig. 3) (PV Capacity 2021).

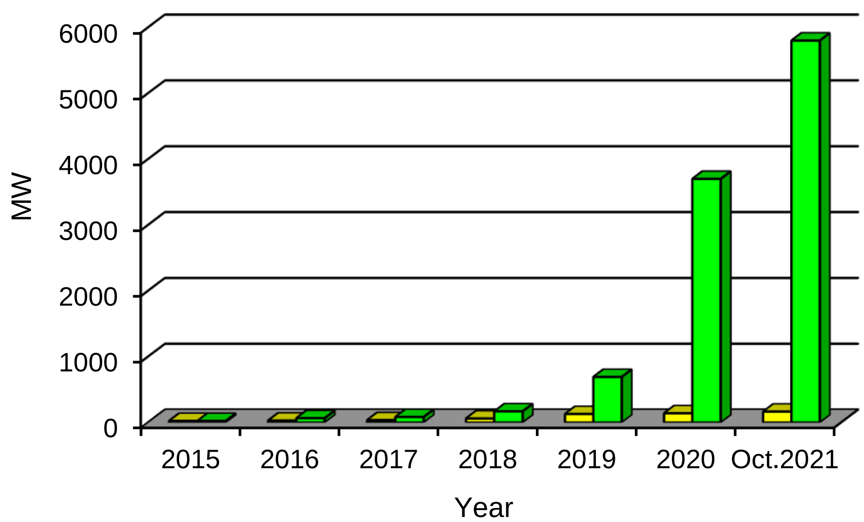

Fig. 3. Power installed in a given year, yellow color – systems over 50 kW, green color – micro-systems (own study from (IRE 2021, PV capacity 2021)

In the medium term, there are no indications of a slowdown in the solar market. PV farm projects prepared for RE auctions, including large-scale ones, will have the main share in the increase in power in the coming years. Even if the pace of development of micro-systems slows down temporarily, the PV as a whole will not be affected by this fact in the next few years. It is a flexible, scalable technology, operating in several segments and many market niches. Additionally, the role of business prosumers is bound to increase this year, with IRE forecasts (IRE 2021) related to them increasing by at least 200 MW, and this trend will intensify further in the coming years (Bukowski et al. 2021). According to the IRE (IRE 2021) forecast, 2022 installed PV capacity will be double its value from late 2020, and by late 2025, it may even reach as much as 15 GW (IRE 2021).

The amount of energy produced (including in the form of auto consumption) in monthly cycles by PV systems in Poland in 2021 was estimated based on the IRE (IRE 2021) forecast for the development of the PV sector. The estimated total amount of energy produced from PV sources in 2020 was 2,374 GWh and was much higher than in the previous year (711 GWh). In 2021, according to the IRE simulation, PV generation will amount to approximately 5,289 GWh (Fig. 4). In 2020, 1.5% of the electricity produced in the country came from PV sources. In 2021, it will be 3.5% while in 2025 solar energy will provide about 10% of Poland’s electricity.

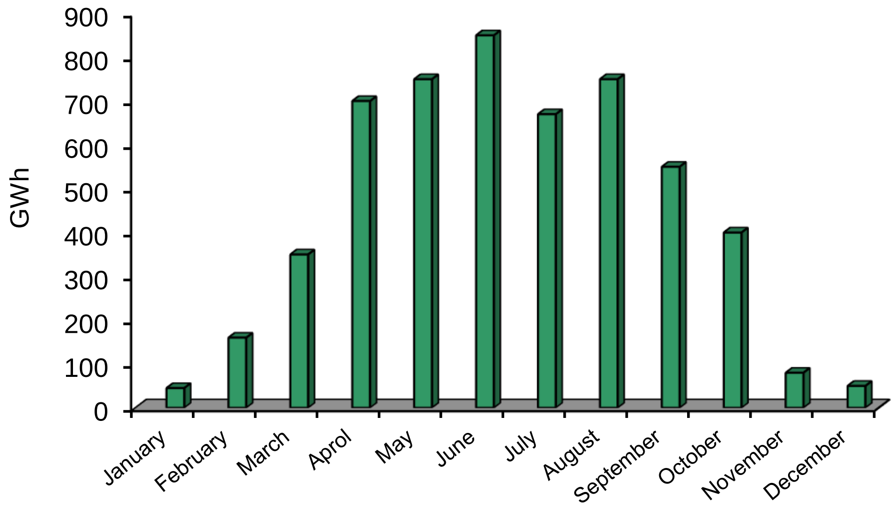

Fig. 4. Estimated amount of electricity from PV systems produced in Poland (own study from (IRE 2021))

Even with the current pace of development, PV is neither the sole nor even a sufficient solution to achieve the EU target by 2030. However, it is the only rational solution with a sufficiently short investment cycle to increase the share of RE in the short term (2022 and 2025), particularly in the electricity generation and consumption segment. This will be achieved primarily through the increase in PV farm capacity in the coming years (IRE 2021).

Poland's 2020 PV investment projects were focused on individual and business prospects, i.e., on the micro and small systems sector (Bukowski et al. 2021). Subsequently, between 2021 and 2022, with deadlines for projects that had won auctions between 2018 and 2019 growing ever closer, a significant part of the investment activity will concentrate on the PV sector. In 2019, PV recorded the largest increases in installed capacity among all RE sources. This means that it is now the primary area of RE investment. In Poland, the total installed PV capacity may reach 8-10 GW by 2025; this means that PV farm capacity could exceed that assumed in the National Energy and Climate Plan for 2030 (IRE 2020) as early as in 2025.

The new production capacity installed in Poland in 2020 is entirely focused on silicon technology. Despite being the most prolific one in the PV market, this technology does not depend on rare or toxic materials, or even ones that are key for other industries (such as cadmium in CdTe cells or indium in CIGS cells) (Mik et al. 2021). The process of increasing the production capacity of "silicon" production lines has progressed evolutionarily for many years (IRE 2020).

Five years after the announcement of the first auctions, the auction system has become the most important instrument to support the PV market in Poland. In 2020, the RE auction basket for solar and wind technology with a capacity of less than 1 MW was once again dominated by solar energy. The 2019 auction for projects above 1 MW was won by only 3 solar farm projects, but it was a harbinger of increasing competition of solar technology in this basket. In the 2020 RE auction, PV systems shared the available volume with wind farms nearly 50/50. The distribution of auction prices for a large basket of winning bids shows that large solar and wind projects offered prices at a similar level. This confirms the thesis about the similarity of these markets and the fact that these technologies can already fully compete with each other, and also that one can expect increasing auction volumes for large-scale PV projects (IEO 2020).

The main share in this power increase in 2021 will be the auction projects from the 2018 and 2019 auctions. The projects that won the 2018 RE auction and had 18 months to start producing energy could apply for an extension of this deadline by one year to the Energy Regulatory Office. While most of the projects were completed in the 2019-2020 period, investors still have time to complete the remaining projects by the end of June 2021. IRE estimates that around 40 MW of such projects remain (out of the 514 MW that won the 2018 auction). On the other hand, 2021 is the year of implementation of mainly 2019 auction projects, which had 24 months to start generating electricity. In total, about 790 MW of such projects from the 2019 auction may be built, including about 64 MW of solar farms from a large basket. The IRE (IRE 2021) estimates that thanks to the implementation of auction projects, the power generated in Poland by solar farms alone may increase by 830 MW in 2021.

A total of six companies in Poland produce PV modules. Most of them develop dynamically, constantly increase their production capacity, and have been on the market for almost 10 years. The manufacturing plants of Polish companies are equipped with automated production lines with a production capacity ranging from 50 to 120 MW/year. Their panel manufacturing processes cover all production stages – from the loading of the glass, through the joining of cells, lamination, assembly of frames and junction boxes, to the testing and rapid detection of imperfections and micro-cracks. Producers in Poland also boast the know-how of different generations of PV modules. Polish production plants manufacture not only standard poly- and monocrystalline silicon modules but also glass-glass modules integrated with buildings – including bifacial modules (Kim et al. 2021).

A material production line called Quantum Glass was launched in Rzeszów. "Quantum Glass" is in practice a transparent PV panel that can be installed wherever classic windows are installed today (Quantum Glass 2021).

In Poland, a new type of electronic perovskite labels has been introduced to store shelves. The Saule Technologies solution is a breakthrough technology that combines a perovskite solar module with an e-ink display with very low power consumption. Perovskite modules are able to generate energy in an artificial environment and in low light (Perovskite labels 2021).

The Polish PV industry has a relatively strong position in the production of PV components (except for cells), but the greatest added value is found upstream in the supply chain and the value chain, i.e., in the production of PV modules.

In 2019, the total sales of PV modules at Polish companies amounted to about 460 MW. The total sales to the Polish market reached about 425 MW. More than half of the modules imported to Poland are from Germany; direct purchase from China is about 15%. Imports from Italy also ranked at a similar level. Polish companies were responsible for almost 15% of supplies to the prosumer market (and this market is traditionally preferred) (IRE 2020).

Development of PV prosumers in Poland

From a niche area, the PV sector has turned into a new fad as owning solar panels has become "trendy" in Poland (Grębosz-Krawczyk et al. 2021). So eager are Polish people to install PV panels that solar energy development forecasts for Poland have already been exceeded many times. Decreasing prices and government programs such as "My Electricity" have contributed to this as well (My Electricity 2021).

The reason behind the rapid increase in the number of micro-systems is the typical Polish prosumer activity. Unlike that in other European countries, Polish PV is clearly much more dispersed, which results from the interest of citizens in producing energy on their own and on a small scale (IRE 2020).

According to the RE Act (RE Act 2015), a RE prosumer is a final customer who produces electricity exclusively from RE for his own use in a micro-system (with a maximum capacity of 50 kW) and who can store or sell that electricity to an obliged seller or another seller, provided that this does not constitute one's predominant business activity – in the case of a final customer who is not a household electricity consumer. Since mid-2019, there have been no objections to entrepreneurs being included in the definition of a prosumer (Szeląg-Sikora et al. 2021). This is a very important change because it has enabled companies to benefit from a system of discounts. Thanks to this system, both companies (so-called business prosumers) and individuals (individual prosumers) can feed surplus electricity into the grid. It is worth noting that within the meaning of the RE Act, a RE prosumer is any final customer ~~(...)~~ who produces energy from RE for his own use and who can store or sell it, provided that – in the case of RE prosumers who are not households – these activities do not constitute his main commercial or professional activity (IRE 2020).

Micro-systems do not require a building permit or an energy production license. Additionally, the investor does not pay the connection fee and does not bear the costs of installing a two-way meter. Unfortunately, unlike a household, a business prosumer typically cannot benefit from income tax relief or a "My Electricity" subsidy (My Electricity 2021). Therefore, since 2019, the number of individual prosumers in the micro-system segment has been growing faster compared to business prosumers.

In Poland, PV micro-systems have the largest market share, accounting for over 90% of the installed PV capacity in 2021. Figure 5 shows the number of PV micro-systems established in Poland in the 2012-2021 period. In October 2021, there were about 700,000 micro-systems in Poland (PV capacity 2021). This means that, on average, every 10^{th} single-family residential building in Poland has a PV system installed.

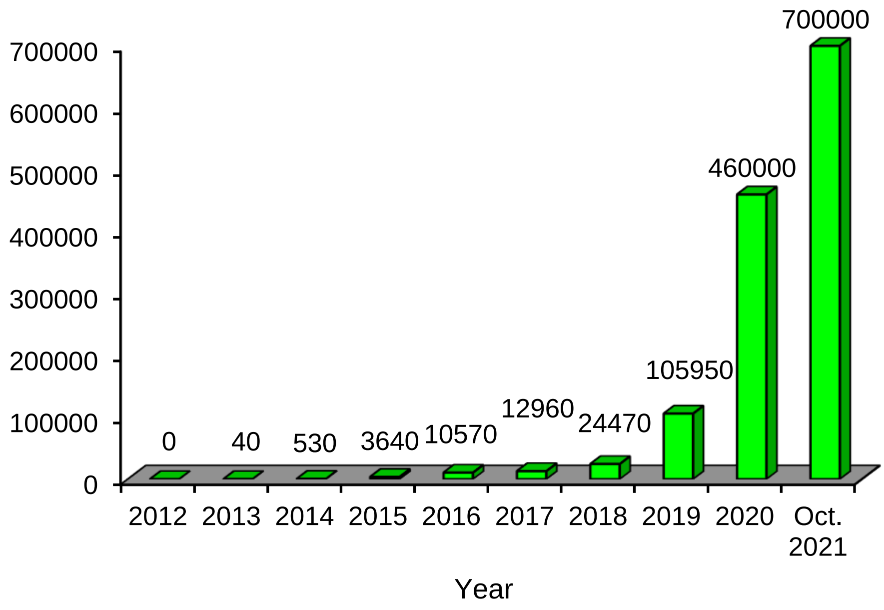

Fig. 5. Number of PV micro-systems established in Poland in specific years (own study from (PV capacity 2021))

An important factor that motivates prosumers is the profitability of such an investment – PV panels allow them to pay less for electricity. Importantly, their cost can be recuperated after about 7 years while their total life span is 25 years or more (Nehme et al. 2021). Thanks to this, one can enjoy "free" electricity for a long time.

Research on PV market prices was conducted by the IRE for the report "Photovoltaic Market in Poland 2020" (IRE 2020). Analyzing the data contained therein, it can be unequivocally stated that component prices are getting lower every year. IRE data indicates that the average price for a 3 kW micro-system is currently about PLN 15,500. It is important to note that the range of prices provided was wide, especially for smaller systems.

According to a report by the Association of the Photovoltaic Industry Poland PV (Association of the Photovoltaic Industry 2020), in 2019, the estimated cost of building 1 kWp of PV micro-systems was PLN 4,125 net, i.e., about 5% less than a year before. The value of the PV micro-system market in Poland has increased over the last year from PLN 730.8 million to PLN 2,852 million, which is an enormous increase of about 290%.

Examples of PV systems in Poland

The FRoSTA company from Bydgoszcz (Kujawsko-Pomorskie Voivodeship), a frozen food manufacturer, has been using its own solar system for a decade now (Fig. 6). The primary motives behind the investment were a reduction of electricity bills and environmental concerns. Situated on the FRoSTA plant's roof, the 80.5 kW PV system covers an area of nearly 600 m^2. All energy generated by the system is used solely by the plant itself. (Igliński et al. 2013).

Fig. 6. PV system, FRoStA company (a photograph provided by FRoSTA).

The Heat Energy Company in Pisz (Warmińsko-Mazurskie Voivodeship) apart from producing ecological heat from waste biomass, also has a 50 kW PV plant on the roof (Fig. 7) (Igliński et. al 2020).

Fig. 7. A private investor's roof PV system, Pisz (photo: W. Kanarek).

Poland's pioneer in the installation of autonomous hybrid solar lamps (Fig. 8) is the municipality of Kowalewo Pomorskie (Kujawsko-Pomorskie Voivodeship). There, 83 such lamps were set up in the 2010-2011 period, with a further 97 added in 2013. The lamps enable significant savings, as one does not need to pay for electricity. (Igliński et al. 2013).

Fig. 8. Hybrid lamp in Kowalewo Pomorskie (photo: B. Igliński).

Torun's Municipal Bicycle system has as many as 40 stations powered by PV systems (Fig. 9), offering 410 bicycles for rental. This includes 10 electrically-assisted ones (so-called 5th generation electric bikes). (Toruń City Bike 2021).

Fig. 9. PV micro-system powering the bicycle control panel, Toruń (photo: B. Igliński).

Programs supporting PV in Poland

To encourage Poles to invest in PV, several programs were created to provide financial support for such investments. It is they, combined with media promotion, that have led to the acceleration of PV investments in Poland.

The Act on Renewable Energy Sources (RE Act 2015) introduced the so-called discount system for owners of photovoltaic installations. For each 1 kWh of energy supplied to the power grid, we will collect 80% of it, while 20% of this energy is given to the power industry in exchange for its storage (in the case of ON-GRID PV installations with an installed capacity of no more than 10 kW). Energy can be collected as part of the annual settlement, then the surplus is lost (it becomes the property of the energy sector). Therefore, it is particularly important to properly select the size of the PV installation, which should not be expected to generate more annual energy than the building's annual energy demand. Otherwise, the economic effect will worsen - the payback period of the investment will be extended. In order to be able to settle accounts under the "old" rules, it is necessary to introduce energy into the grid before April 1, 2022. The new method of settling accounts with energy companies is to be based on the net billing principle. Prosumers will sell the surplus of produced energy to the grid at wholesale prices, and when they take electricity from the power grids, they will pay at retail rates.

According to (PV calculator 2022), PV brings savings of PLN 2,376 in the first year of operation. On average, you need to pay about PLN 25,000 for 5 kW PV panels with assembly and really good quality equipment. It is a home PV power plant that will meet the needs of a family with children living in a medium-sized house. With current settlements, an individual PV installation will pay for itself after about 10 years. The payback time may be shorter if co-financing is included in the financial account.

The „My Electricity" program

"My Electricity" program (My Electricity 2021) makes it possible to obtain a subsidy for the construction of PV micro-systems (from 2 kW to 10 kW); such a subsidy can reach up to 50% of eligible costs, but no more than PLN 5,000 per project (PLN 3,000 in 2021). The first call for proposals took place between August 30, 2019, and December 20, 2019. The second call for proposals started on January 13, 2020, and ended on December 6, 2020. According to government announcements, the latest edition of the program started in July 2021. In total, approximately 27,000 PV projects with a total capacity of 152 MW were awarded funding. The total number of grants awarded as of May 17, 2021, reached 199,000. The program is addressed to natural persons generating electricity for their own needs who have concluded a comprehensive agreement (with the Distribution Network Operator and the power plant) regulating the issues related to the feeding of electricity generated in a micro-system into the network. The subsidy is exempt from PIT (My Electricity 2021).

The call for proposals has the form of a competition – the best marks are given to projects that cost less than PLN 6,000 per 1 kW; thus, such projects have the greatest chance of receiving co-financing. The program's budget for 2019-2025 is PLN 1 billion (Olczak et al. 2021). The second call for proposals runs from January 13, 2020, to December 18, 2020, or until all funds are allocated (My Electricity 2021).

Figure 10 presents the results of the "My Electricity" program as of June 4, 2021. The green color indicates the number of grants awarded for PV system projects, while the black color shows the combined power of the system in a given voivodeship [kW]. It is worth noting that the largest number of granted subsidies (25,354) and the largest PV power (147.1 MW) is in the Śląskie Voivodeship – a voivodeship with coal mines and power plants. In this case, one can say that this marks the beginning of Śląskie Voivodeship's energy transformation (My Electricity 2021).

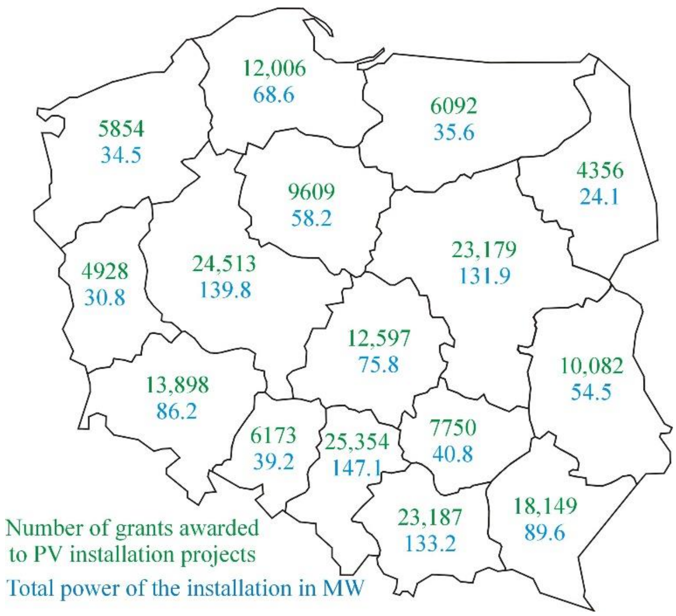

Fig. 10. Number of subsidies awarded (green) and power of PV systems created by the "My Electricity" program (own study from (My Electricity 2021))

Undoubtedly, the “My Electricity” program and its nationwide promotion have had a positive impact on the reception of PV technology and its social acceptance. Additionally, the emergence of an increasing number of systems in households promotes the acceptance of PV roof systems as a permanent element of the landscape (My Electricity 2021).

“Energy Plus” program

One of the leading programs aimed at businesses is “Energy Plus”, which aims to reduce the negative impact of companies on the environment, including improving air quality. The program’s budget is PLN 4 billion, of which PLN 50 million is earmarked for non-refundable forms of co-financing, and PLN 3.95 billion for repayable forms. The amount of the loan that can be received ranges from PLN 1 million to PLN 300 million (Energy Plus 2020).
Beneficiaries are required to meet the following conditions:

- the average final energy consumption in the year preceding the application for co-financing must have been at least 2 GWh/year,
- submission of the application to the program must have been preceded by an energy audit,
- planned energy savings must be no lower than 5%.

The call for proposals ran until December 18, 2020 (Energy Plus 2020).

“Agro-energy 2021” program

The “Agro-energy 2021” program (Agro-energy 2021) aims to increase the production of energy from RE sources in the agricultural sector. Its beneficiaries are individual farmers who own a total agricultural area ranging from 1 to 300 ha. They may receive a subsidy of up to PLN 15,000 (for systems over 10 kW but less than 30 kW) or PLN 25,000 (for systems between 30 and 50 kW). For those who opt for the construction of a hybrid system (PV with a heat pump), an allowance of PLN 10,000 is provided). Importantly, the project cannot be started before the date of submission of the funding application. The total budget of the program amounts to PLN 200 million (PLN 170 million in non-refundable and PLN 30 million in refundable forms of co-financing). Contracts will be signed until 2023 and disbursement of funds will be completed two years later (Agro-energy 2021).

"Clean Air" program

The aim of the "Clean Air" program (Clean Air 2020) is to improve air quality and reduce greenhouse gas emissions by exchanging heating sources and improving energy efficiency in single-family residential buildings.

The program aims to support projects involving the dismantling of inefficient solid fuel heating sources and the purchase and installation of air-to-water or ground source heat pumps to provide heating or both heating and hot water. Additionally, PV micro-systems can also be purchased and installed as part of the program. The maximum subsidy amount is PLN 30,000 – for projects including a PV micro-system (Clean Air 2020).

Program beneficiaries are natural persons who are owners/co-owners of single-family residential buildings or single-family residential units with separate land and mortgage register entries and an annual income not exceeding PLN 100,000 (Clean Air 2020).

Tax reliefs

The Act of January 1, 2019, (Act 2019) introduced a new subjective exemption in personal income tax and the so-called thermo-modernization relief. The thermo-modernization relief consists in deducting from the tax calculation basis an amount of up to PLN 53,000 with respect to all thermo-modernization projects carried out in individual single-family buildings of which the taxpayer is the owner or co-owner. Deductibility is available to taxpayers who tax their income according to the tax scale or at a uniform 19% tax rate and pay a lump sum on recorded income. Deductible expenses must be incurred for the implementation of the thermal modernization project, including PV. The deduction amount which is not covered by the taxpayer's annual income will be deductible in subsequent years, but no longer than for 6 years, counting from the end of the tax year in which the first expenditure was incurred (Act 2019).

The second form of tax relief introduced in 2019 was the inclusion of PV house systems in the reduced VAT rate. Under the amendment of October 16, 2019, to the Environmental Protection Law (Environmental Protection Law 2001), the VAT rate for RE systems was reduced from 23% to 8%. The supply and construction of a micro-system to provide energy for such buildings is subject to a single reduced tax. The only limitation is the area of the residential building to which the PV system is functionally linked, which may not exceed 300 m^2.

Technical potential of PV in Poland

The potential of PV in Poland has been calculated with the assumption that public buildings, newly erected buildings, and wastelands will be used for this purpose (Angowski et al. 2021). This will allow the development of PV, while at the same time the land for PV systems will not be taken away (Jurasz et al. 2020).

Technical potential of PV obtained on roofs in Poland

In an effort to reduce costs, public utility buildings opt to install more and more PV panels on roofs. It was assumed that 10% of public facilities will install PV panels, with their roof surfaces used for calculations. The following roof surfaces were adopted for this purpose: schools: 1,000 m^2, kindergartens: 250 m^2, nurseries: 150 m^2, accommodation facilities: 500 m^2, culture centers: 250 m^2, offices: 300 m^2, hospitals: 500 m^2, clinics: 300 m^2, pharmacies: 100 m^2, pharmacy points: 50 m^2, shops: 100 m^2, catering and restaurants: 100 m^2, churches: 1,000 m^2 and petrol stations: 250 m^2 (Igliński 2019).

Additionally, 5% of the area of Poland's building roofs was included. Formula 1 was used for calculations of E_r.

$$E_r = 0.05 \cdot A_r \cdot S \cdot I \cdot E \quad (1)$$

where: E_r – energy obtained from roofs [TJ], A_r – area of roofs [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Also, 10% of the area of newly erected buildings in Poland was included (in a 10-year perspective) (Igliński 2019). Formula 2 was used for calculations of E_r.

$$E_{rn} = 0.1 \cdot A_r \cdot S \cdot I \cdot E \quad (2)$$

where: E_{rn} – energy obtained from roofs [TJ], A_{rn} – area of roofs [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Table 1 shows the available area and technical potential of roof PV in Poland.

Table 1. Available area and technical potential of PV on roofs in Poland (own study)

Object	Available area [thous. m^2]	Amount of electricity [TJ]
schools	1,614	1,800
kindergartens	148	164
nurseries	23	26
accommodation facilities	267	299
culture centers	77	86
offices	42	46
hospitals	52	58
clinics	320	356
pharmacies	73	82
pharmacy points	3	4
shops	1,300	1,450
catering and reataurants	355	396
churches	512	672
petrol stations	114	128
operating railway stations	23	26
other buildings	76,250	42,499
newly built buildings (in the perspective of 10 years)	37,390	20,840
Summary	**118,563**	**68,932**

The total PV technical potential of PV on roofs is 68,932 TJ (6.89 TWh). It would make it possible to cover 4.21% of electricity needs (in 2019, 163.7 TWh of electricity was produced in Poland) (Statistics Poland 2020c).

Poland has a large area of wastelands, amounting to 63,374 ha (Statistics Poland 2020c). It was assumed that it is technically possible to reclaim 10% of the wastelands for energy generation purposes and build solar power plants on them. Sunshine and insolation of individual areas of Poland were taken into account (data obtained from the Institute of Meteorology and Water Management); afterward, the amount of electricity that can be obtained using photovoltaic panels with a 15% efficiency was calculated using formula 3:

$$E_w = 0.1 \cdot A_w \cdot S \cdot I \cdot E \quad (3)$$

where: E_w – energy obtained from wastelands [TJ], A_w – area of wastelands [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Collectively, it is possible to obtain 3,169 TJ (880 GWh) of electricity across Poland – the most in the Wielkopolskie (512 TJ) and Dolnośląskie (397 TJ) voivodeships (Figure 11).

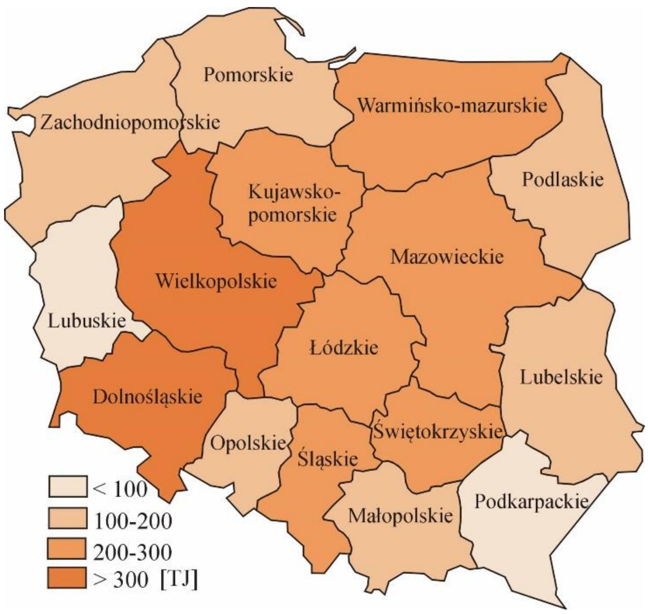

Fig. 11. Distribution of the amount of energy that can be obtained annually from PV panels on Polish wastelands (own study)

The data from Statistics Poland (Statistics Poland (2020b)) and information provided by the Marshal's Offices of individual voivodeships (Igliński 2019) were used to calculate the PV potential. 1.5 million ha of municipal landfills have been closed in the last 10 years. They are currently being reclaimed or their rehabilitation has been completed. It was assumed that 10% of the area of these landfills is technically possible to be covered with PV panels (the area of the entire power plant may be slightly larger due to the necessary technical spacing between the rows of panels). It was calculated how much electricity E_{cm} can be obtained with the efficiency of PVpanels 15%, using the formula 4:

$$E_{cm} = 0.1 \bullet A_{cm} \bullet S \bullet I \bullet E \quad (4)$$

where: E_{cm} – energy obtained from closed municipal waste landfills [TJ], A_{cm} – area of closed municipal waste landfills [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Using PV panels in landfills in Poland, it is possible to obtain a total of 836 TJ (232 GWh) of electricity, with the highest number in the Warmińsko-Mazurskie (129 TJ), Dolnośląskie (99 TJ), and Pomorskie (99 TJ) voivodeships (Fig. 12).

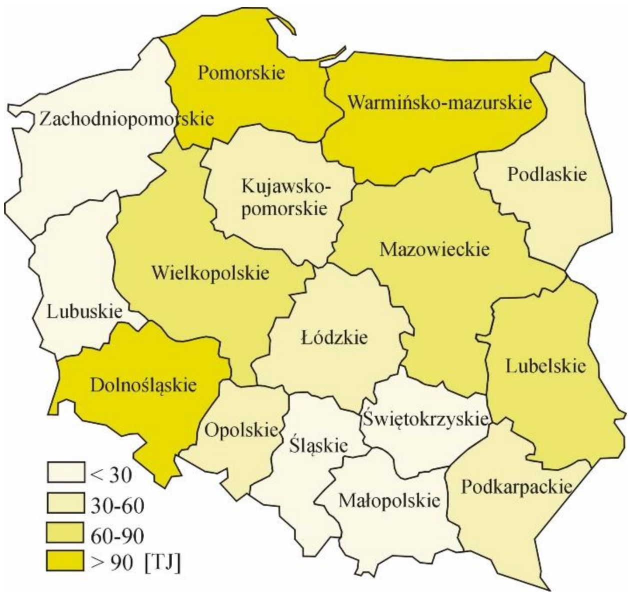

Fig. 12. Distribution of the amount of energy that can be obtained annually from PV panels in closed municipal landfills in Poland (own study)

Ultimately, in the next 15-20 years, all municipal waste landfills operating today will be closed (Igliński 2019). One of the directions of landfill rehabilitation should be energy production. It was assumed that 10% of the area of these landfills is technically possible to be covered with PV panels. Sunshine and insolation of individual areas of Poland were taken into account (data obtained from the Institute of Meteorology and Water Management), and then the amount of electricity that can be obtained with the efficiency of PV panels of 15% was calculated, using the formula 5:

$$E_{wp} = 0.1 \bullet A_{wp} \bullet S \bullet I \bullet E \quad (5)$$

where: E_{wp} – energy obtained from municipal waste landfills planned to be closed [TJ], A_{wp} – area of municipal waste landfills planned to be closed [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

In all of Poland, a total of 1037 TJ (288 GWh) of electricity can be obtained, with the greatest number in the Wielkopolskie (121 TJ), Mazowieckie (99 TJ), Dolnośląskie (98 TJ) and Kujawsko-Pomorskie (90 TJ) voivodeships (Fig. 13).

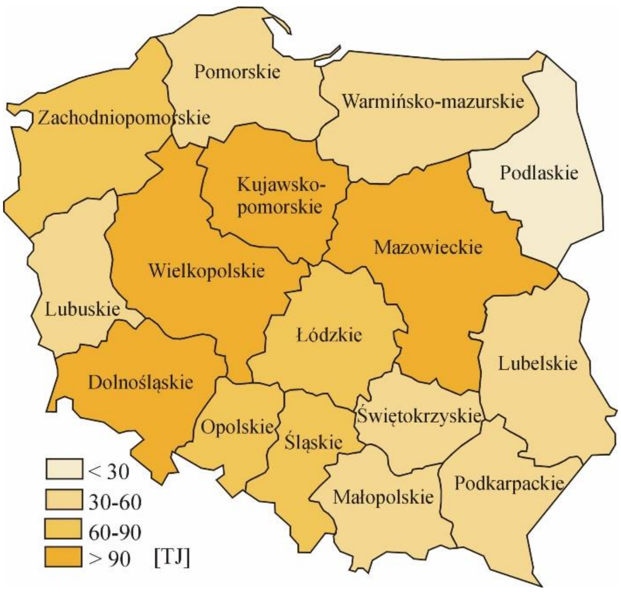

Fig. 13. Distribution of the amount of energy that can be obtained annually from PV panels at Poland's municipal landfills planned to be closed (own study)

PV systems on highways and expressways in Poland

Poland has approximately 7,800 km of major roads, which includes about 2,000 km of motorways and nearly 5,800 km of expressways (Igliński 2019). It was assumed that it is technically possible to build 10 m wide PV panels along 10% of the total length of highways and expressways. The amount of electricity that could be obtained from PV panels with a 15% efficiency was calculated using formula 6:

$$E_{he} = 0.1 \bullet A_{he} \bullet S \bullet I \bullet E \tag{6}$$

where: E_{he} – energy obtained from highways and expressways [TJ], A_{he} – area of highways and expressways [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Based on the calculations, the amount of obtainable electricity is 4.35 PJ (1.21 TWh). It could be used to power traffic lights, roadside bars, restaurants, etc.

PV systems at railway lines in Poland

The length of railway lines in Poland is 22,022 km (Igliński 2019). It was assumed that it is technically possible to place 10 m wide PV panels along 10% of the total length of railway lines. The amount of electricity that could be obtained from PV panels with a 15% efficiency was calculated using formula 7:

$$E_r = 0.1 \bullet A_r \bullet S \bullet I \bullet E \tag{7}$$

where: E_{he} – energy obtained from railway lines [TJ], A_r – area of highways and expressways [m^2], S – sunshine [h/year], I – insolation [W/m^2], E – efficiency.

Based on the calculations, the amount of obtainable electricity is 12.28 PJ. It could be used by Polish State Railways, with any potential surplus being sold.

Summing up, the technical potential of PV in Poland is 75.16 PJ (20.94 TWh). It would cover 12.8% of Poland's electricity needs (in 2019, 163.7 TWh of electricity was produced in Poland)

(Statistics Poland 2020e). This potential can be increased by using a greater roof or wasteland area for PV purposes.

SWOT analysis for PV in Poland

SWOT analysis is a comprehensive strategic analysis method, which includes examining both the interior and exterior of a business or organization (Qaiser 2022). It consists in identifying key strengths and weaknesses and confronting them with current and future opportunities and threats. SWOT analysis is one of the most used tools of strategic analysis (Mukeshimana et al. 2021). Based on the SWOT analysis, a set of the following is obtained: **S** (Strengths) – strong suits to be reinforced, **W** (Weaknesses) – weak points to be reduced, **O** (Opportunities) – opportunities to be exploited, **T** (Threats) – threats to be avoided (Fig. 14) (Igliński et al. 2016b). Table 2 shows the SWOT analysis of PV in Poland.

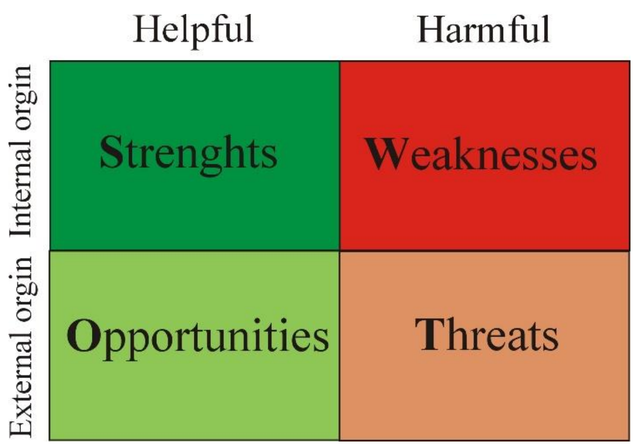

Fig. 15. SWOT analysis diagram (own study).

Table 2. SWOT analysis of PV in Poland (own study).

Strengths	**Weaknesses**
• high level of social acceptance • significant potential • possibility of use in places not connected to the power grid • low system operating costs	• high costs of PV systems • problems during system assembly • disparities in the amount of solar energy reaching the system in the spring/summer and autumn/winter seasons

• low solar system failure rate and low maintenance needs • investment support programs • can be combined with other systems, e.g., with a heat pump	
Opportunities	**Threats**
• rapid technological progress, increasing efficiency and reducing the cost of solar systems • perovskite development • progress in energy storage technology for autonomous systems	• climate change • smog in the autumn and winter period • coronavirus pandemic • decline in efficiency

Strengths

Among all types of RE, it is PV that enjoys the greatest social support in Poland. A survey by the Public Opinion Research Center called "Poles about energy sources, energy policy and the state of the environment" (Public Opinion Research Center 2016) showed that Poles strongly prefer PV systems (73%) among all RE sources.

In the case of Poland, one of PV's advantages is the fact that the installation of PV panels together with an energy storage system provides electricity in places where access to the power grid is difficult, such as mountain hostels (Hassan 2021).

Other strong suits include low operating costs, low maintenance needs, and low failure rates of solar systems.

Yet another advantage of the PV sector in Poland is the fact that as of today, investors can benefit from several programs supporting PV investment projects, such as the "My Electricity" program (My Electricity 2021). Furthermore, they can benefit from tax reliefs as well.

Combining PV systems with other RE systems, e.g., with heat pumps (You et al. 2021) is becoming increasingly popular in Poland. A PV system provides electricity for the heat pump, which in turn provides heat for the house (Vaishak and Bhale 2021).

Weaknesses

PV systems are still quite expensive, which is why few private individuals opt for them without first securing funding. The prices of PV systems start from about PLN 15,500 for 3 kW panels (Igliński 2019). A common issue complicating the panels' installation is having an old, deteriorated roof. Roofs are often in such a bad condition that they must be sealed or even replaced before installation. Additionally, PV systems must be installed at the right angle.

Other weaknesses include large disparities in the amount of solar energy reaching the panels throughout the year due to Poland's climatic conditions. Most of the total annual sunshine is available in the six months of the spring/summer season – from early April to late September – with as many as 16 solar hours per day; in the winter, this is reduced to 8 hours per day (Igliński et al. 2013).

Opportunities

Many scientific centers are working to improve existing materials or develop new materials for solar systems all over the world (Magadley et al. 2022). One such solution – perovskites – may soon revolutionize PV (Vesce et al. 2021). The advantages of these minerals are indeed many, with the most important ones being high light absorption capacity, flexibility, transparency, and lightness. Perovskite cells can be used to cover a wide range of materials – from thin PET films to tiles and walls to clothes and electronics. In this way, each of these objects can become a miniature power plant producing clean energy (Shariatinia 2020).

Since 1977, the price of a photocell per unit of electric power has fallen nominally by about 250 times – from USD 76 to about 30-35 cents per watt. It is worth noting that the real decrease in this price was even greater since the value of money, including the US dollar, has dropped significantly over the last 30 years (Solar PV module costs 2020). If the trend of falling prices of PV cells is maintained, electricity from PV modules will soon be significantly cheaper than that produced from fossil fuels (Brodziński et al. 2021).

The opportunities include the fact that the decrease in the price of PV cells in the last three decades has been accompanied by a several-fold increase in their efficiency, which nowadays is in the order of 10-30%, and reaches nearly 50% in the case of the most efficient ones (four-connector cells with a so-called concentrator) (National Renewable Energy Laboratory 2021).

Work is also underway on household electricity batteries and hydrogen production (Sarkarzadeh and Farsi 2020). One such solution is the Powerwall, which is only 130×86×18 cm in size and weighs about 100 kilograms, but can store 10 kWh (Future Tech. 2020).

Threats

The threats include the progress of climate change (Salvia et al. 2021). The most important projected impacts for Central and Eastern Europe include more frequent temperature extremes, higher precipitation intensity that can cause floods at any time of the year, as well as increased frequency and intensity of hurricanes. Hurricanes, tornadoes, and hailstorms can prove devastating to PV plants.

In Poland, smog appears in the autumn and winter – particularly in cities. Polluted air negatively affects solar panel performance (Palmer 2019).

The three waves of coronavirus in Poland slowed down PV investment projects to some extent. If another lockdown is imposed, the situation may repeat itself – some investment projects may be delayed or outright canceled.

Except for tracking lugs on panels that are installed on the ground or on poles, PV systems have no moving parts. This makes breakdowns due to wear extremely unlikely, but the chemicals used to manufacture the panels can deteriorate over time. However, a photovoltaic system does not age suddenly. Its power gradually diminishes, which is called degradation. PV panels used in Poland in 2020 have a minimum guaranteed lifetime of 25 years. The rate of panel degradation may vary by brand. According to research by the National Renewable Energy Laboratory, panels from premium manufacturers enjoy less degradation, up to 0.3% per year. Unfortunately, some brands have a much higher degradation rate as high as 0.8% per year, but 0.5% is an average rate. At the end of the 25-year warranty period, with an average degree of degradation (0.5%), the panels can still operate at approximately 88% efficiency. The actual service life of the panels can be much longer (National Renewable Energy Laboratory 2021).

Discussion and summary

So far, PV development in Poland has been based mainly on micro-systems that Poles increasingly often install on their rooftops, as well as and systems up to 1 MW, which have received a guarantee of support in auctions.

The auctions planned for December 2020 could contribute an additional 750 MW of smaller PV systems, i.e., ones below 1 MW. A new phenomenon may also be the development of large-scale PV farms. The ambitious plans of an increasing number of investors, including state-owned energy companies, suggest that PV may be able to compete effectively with wind power in auctions for projects above 1 MW. In this case, the average cost of electricity would have to be less than PLN 285 per MWh.

The prosumer sector not only drives the development of the Polish PV market but also builds social support for the idea of proprietary energy production. While only around 4 PV micro-systems were created in Poland by 2015, there are now (October 2021) around 700,000 such systems. As a result of the rapid development of the PV market, the growth in domestic PV power may be faster than projected by the government in the national energy and climate plan.

For the first time, the Polish market for terrestrial PV farms is almost entirely based on the auction system, in which investors receive 15-year guarantees to sell energy at prices offered at the auctions. As a result of the 2016 auction, 68.4 MW of PV projects received support; in 2017 it was 289.4 MW; in 2018 – 514.1 MW; and in 2019 already as much as 792.5 MW. It is in the PV sector that investments will take place in the 2021-2022 period when the auctioned projects are put into operation. The PV market will change from a typical prosumer market to a more sustainable one – it will become distributed between both professional PV power stations and prosumers themselves. Soon, huge PV farms may also be built, for which there may be a place in the auction system when the supply of finished wind farm projects is exhausted.

The construction of PV farms has also been announced by large players, including state-owned companies. For example, the Polish Energy Group – Poland's largest energy company – intends to build systems with a capacity of up to 2.5 GW within a decade.

The previously calculated potential of PV was 153.484 PJ (42.634 TWh) and would cover 26.04% of Poland's electricity needs (Table 3). Covering the roofs of detached houses and apartment blocks would increase this potential even further. Poland's energy transformation should proceed towards an RE energy mix supported by energy storage facilities.

Table 3. Total technical potential of PV in Poland

Localization	Energy [PJ]
PV on roofs in Poland	68.932
PV on wastelands	3.169
PV at closed municipal waste landfills	0.836
PV systems at municipal waste landfills planned to be closed	1.037
PV systems at highways and expressways	4.350
PV systems at railway lines	75.160
Total	**153.484**

The SWOT analysis shows that there are currently good conditions for the development of PV in Poland. It should be stated that PV's rapid development is bound to continue. This is facilitated by high social acceptance, support programs, and a low failure rate of PV systems. Rapid technological progress increases efficiency and reduces the cost of solar systems as well. Due to the large disparities in the amount of solar energy available in the spring-summer and autumn-winter seasons, PV should be supported by other types of RE. High expectations are connected with the development of offshore wind energy in Poland and the further development of agricultural biogas plants.

The COVID-19 crisis, and particularly the production of PV equipment which is dominated by China – the first country to be affected by the pandemic, demonstrated the need to shorten the supply chain and move production to where there is demand for industrial products. European companies and scientific institutions have recognized the need for active action to develop the PV industry in the EU. Over 90 EU companies and research institutions have signed the Solar Europe Now declaration. Enjoying strong support of the industry, including 6 Polish companies, the coalition strives to use the instruments of the European Green Deal for reindustrialization and prove the economic viability of the production in the EU of all components necessary for PV.

Apart from the draft EU budget for 2021-2027, which is traditionally "green" (with Poland set to receive over EUR 60 billion), the European Commission prepared a "Recovery Plan" (after the pandemic and the economic crisis that it brought about) to the tune of EUR 750 billion, which is also to be closely linked to the implementation of the Green Deal. The green economy is becoming an increasingly important component of European pro-climate and anti-crisis action (together with the new EU industrial strategy), as well as a key element of the energy transition process.

It is also worth mentioning the concept of establishing a Polish Giga Factory. It consists in a 10-fold increase in the current national production capacity. The concept also enables launching production at various points in the technological line: Silicon crystallization + wafer production + cell production + PV module production. Polish companies are currently focusing on the possibility of increasing the production of modules and cells, but the silicon and non-ferrous metal industries can also expand their production capacity in other elements of the technological process over time.

In 2020, PV became an investment hit in the energy sector and an economic driver in Poland. In the difficult time of two lockdowns caused by the global pandemic, domestic PV made a significant contribution to the maintenance of investment processes in the amount of PLN 9.5 billion and provided Poland with 35 thousand jobs. In 2020, 1.5% of the country's electricity came from PV sources. In 2021, it will be 3.5%, and by 2025, solar energy will provide approx. 10% of Poland's electricity. PV is becoming a permanent element of the national energy system, and during the daily and summer energy demand peaks, it becomes its basis, providing a power reserve and reducing energy costs for the entire energy system – not only for prosumers but for all energy recipients.

In the case of large PV installations, there is a problem where to place them. There is often a shortage of land and ever higher lease prices. A good solution is to locate PV farms in degraded areas or on water (preferably industrial) reservoirs. The advantage of this solution is the cooling of the farm by water, which increases its efficiency on hot days. of land combined with the rising price of land is detrimental to the development of large-scale photovoltaic (PV) power plants. The article (Goswami and Sadhu 2021) presents the use of a PV system in wastewater treatment because relatively large water surfaces are available there. An experiment was carried out to determine the performance of the FSPV system and showed that the in-water PV module performed with a 9.84% higher efficiency than the on-shore PV module. A feasibility study and a technical and economic analysis of a 15 MW water PV system were presented and compared to a similar onshore PV system. The results show that the power plant will supply 26,465.7 MWh of energy annually to the grid. The PV system on water will also save 7,884,000 m^3 of water by limiting evaporation, and the reduction of CO_2 emissions will be 518,943.4 tCO_2. Financial analysis of the PV system on water showed that the LCOE is 0.047 $ / kWh, which is 7.84% lower than the LBPV system.

The article (Bukowski et al. 2021) showed the macroeconomic investment efficiency of PV installations in order in order to meet the demand for electricity in single-family houses in Polish conditions. The conducted analyzes additionally cover the characteristics of the market and legal regulations concerning the sale of electricity in Poland. The simulations were carried out for 320 variants differing in the location of the investment, building orientation and roof slope. The results show that the region is the most favorable for development PV micro-installations are located in south-eastern and central Poland. The highest values of economic efficiency were achieved in the case of the southern roof slope, such as and south-east and south-west orientation of buildings. No major differences were observed in economic investment efficiency for panel inclinations. Discounted cost recovery calculated the period, depending on the calculation method, ranges from 5.4 to 10 years.

Support for the development of PV on the part of the Polish state are programs that subsidize PV installations. The promotion is increasingly noticeable by companies that deal with the production and, above all, assembly of PV installations. Advertising spots on TV, radio and the Internet have become commonplace. What's more, companies call almost everyone with a ready offer. PV companies more and more often support sportsmen, e.g. ski jumpers or employ famous people for advertising. PV is recognized in the EU as crucial for creating a sustainable and secure energy system in the future. All energy scenarios developed in the EU to meet the 2050 climate goals provide a key role for photovoltaics. More than 90 companies and research institutions from 15 EU countries initiated the Solar Europe Now campaign and signed its declaration. According to signatories, solar energy is the key to achieving the goal of climate neutrality by 2050.

It is worth examining the development of PV from a broad and long-term perspective. The spectacular development of PV in Poland is due to hitting the right time window and reducing technology costs, but most of all, it is based on the cooperation of stakeholders and trust in the regulatory environment.

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