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Development of Roadmap for Photovoltaic Solar Technologies and Market in Poland

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Abstract: Poland is dynamically changing its energy mix. As a result of this process, solar energy is increasing its share in energy production. The development of the solar energy market is determined by numerous factors. This paper aims to develop a roadmap for further development of the photovoltaic (PV) energy market in Poland. The scope of the research covers five areas of PV technology and market development in Poland: (i) technology; (ii) power grids; (iii) law; (iv) economic conditions; and (v) social conditions. With the use of a Technology Roadmapping Methodology (TRM), for each of the determined areas, several factors were analyzed, and their development paths were described. In addition, the article focuses on technological challenges (regarding PV cells, modules, components, power conversion and monitoring and management system, optimizers, batteries, and other energy storage systems), grid efficiency, recycling, production costs, subsidies, public awareness and education, and the energy exclusion problem. The main result of the research is the roadmap of the photovoltaic solar energy technology and market development in Poland. Further development of the PV market and technology requires parallel progress in all the identified areas. This study offers implications for policymakers, investors, managers, and technology and infrastructure developers regarding their involvement in photovoltaic market.

Keywords: photovoltaics (PV); solar energy; renewable energy sources (RES); technology roadmapping methodology (TRM); Poland

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1. Introduction

The European Union (EU) is in the process of transformation toward a Circular Economy (CE) model, which is an important part of the newest strategy for the economic growth—European Green Deal (EGD) [1]. In the official documents published by the European Commission (EC), there is a significant need to rethink policies for clean energy supply across the whole economy, with strong focus on industry, large-scale infrastructure, production and consumption, transport, construction, taxation, food and agriculture, as well as with emphasis on citizens [2]. The main objective of the EGD is to achieve climate neutrality in Europe by 2050. However, to meet this ambitious goal, it is required to continue actions on the decarbonization of the energy system [3], which includes the development and implementation of alternative energy production solutions and implementation of renewable energy systems (RES) [4]. It should be stressed that the RES have many potential benefits, including reduction in greenhouse gas (GHG) emissions, diversification of energy supplies and increase of independence on fossil fuel markets, as oil or gas [5]. An important aspect of the growth of RES may also stimulate employment in the European countries, through the creation of jobs in green solutions and technologies [6].

In recent years, a significant increase in the number of alternative energy technologies has been observed, as the share of RES in gross final energy consumption was equal to 21.3% in 2019 in EU, comparing to 19.7% in 2019 and 9.6% in 2004 [7]. This is mainly a consequence of the implementation of the legally binding targets for renewable energy sources, indicated in the Directive 2009/28/EC [8] on the promotion of the use of energy from renewable sources. Despite the fact that all Member States were obliged to develop national programs for the implementation of alternative energy sources, the successes in RES was varied by country, for example, in Finland, Denmark and Latvia, the share of renewable sources exceeded the European average, while in the Netherlands, Poland or Belgium, it was below the average. On the European level, wind power, solar power and solid biofuels are the most widely used sources of renewable energy [7]. The EC indicated an ambitious goal that its 20% of its gross final energy consumption should reach 32% RES by 2030. Therefore, activities for the development of RES technology are one of the key challenges for the Member States, also in the context of implementing the EGD strategy which assumes climate neutrality on the continent up to 2050 [1].

Among the European countries, Poland is an important player in the energy sector as it was the sixth largest electricity consumer in the EU in 2018 [9], and the second country (after Germany) generating electricity based on hard coal (80 TWh) and lignite (49 TWh). Moreover, despite the strong promotion of the RES, there was an increase in the use of hard coal in energy production in Poland (by 2 TWh) in 2018 comparing to the previous year. Due to high emissions of the Polish economy (average 682 gCO_{2eq}/kWh, while the EU average 296 gCO_{2eq}/kWh in 2018) [10] further initiatives to increase the use of energy from renewable sources are strongly recommended. It is defined in the *Energy Policy of Poland until 2040* [11] which is the newest strategy for the fuel and energy sector. The dynamic technological progress observed in the recent years should have a significant impact on the scale of RES use, both in terms of currently known methods of energy production such as wind turbines, solar radiation (photovoltaic panels), or completely new technologies, and in terms of energy storage technologies.

One of the most promising possibilities of decarbonization of the Polish economy is the usage of solar energy sources, such as photovoltaics (PV) [12], which could be applied to power small portable devices, such as calculators or watches, parking meters, lamps, and traffic lights, as well as to heat rooms and water in residential buildings and for industrial installations [13]. At the end of 2020, around 760 GW [14] were installed in the world, covering 3.7% of the world's electricity demand. In 2020, a dynamic development of the photovoltaic industry in Poland was observed [15] that is the total installed capacity of photovoltaics reached 3936 MW, an increase by 2463 MW to the previous year (200% increase). At the end of 2021, the installed PV capacity in Poland is close to 6.5 GW, while in 2025 it may reach 15 GW. At the same time, according to Solar Power Europe, in 2020 Poland was in 4th place in terms of increasing the installed PV capacity in the EU, following Germany, the Netherlands and Spain [16]. Further development of the Polish photovoltaic industry is expected as this sector can guarantee competitive, cheap, safe, and clean solar electricity by 2030. Moreover, approx. PLN 260 billion (~EUR 58 billion) from the EU and national funds under various mechanisms have been planned to be allocated to the national energy and climate transition until 2030 [11]. Therefore, photovoltaics may be a key pillar of the energy system transition to clean and independent energy production based on 100% renewable energy in Poland. By reducing CO_2 emissions, the development of the PV sector is making an important contribution to the fight against climate change. In addition, photovoltaics has a decisive impact on securing energy supplies and the protection of natural resources [17]. It is predicted that higher energy prices, lower installation costs of photovoltaic (PV) systems and government support for photovoltaics will have made it the largest source of electricity, meeting 20% of demand by 2060 [18].

In addition to the increasing number of research and implementation projects devoted to the photovoltaic systems [19], such solutions are also being implemented more and more frequently, both in enterprises and individual households [20]. However, the dynamics and interests in the implementation of photovoltaic systems are not uniform and are also scattered throughout the country. Therefore, it is strongly recommended to develop comprehensive documents in the forms of strategic plans (roadmaps) for the implementation of PV solutions. These documents should determine the main paths of action and accelerate the implementation of photovoltaic technologies based on integrated economic, environmental, legal and social analyses. In the context of the Polish market, perspectives for further development of photovoltaic technologies are expected but are still not fully recognized. Some analyses related to PV technology and market in Poland have been published in both scientific and non-scientific databases. However, they mainly focus only on selected areas of the PV market in Poland. For example, one of the recent analyses [21] investigates employment and domestic production capacity (but omits numerous other factors). There are also some research papers that describe the development of PV installations in country, such as [22,23]. In general, there is a lack of a comprehensive documents that show the various elements of the country's PV market system and this leads to a limited approach to the development of the PV market (e.g., focusing only on specific aspects, such as the efficiency of PV cells) or irregular growth of the PV market in different regions in Poland. To address this research gap, the main objective of the current paper is to develop an integrated roadmap for the photovoltaic solar energy market in Poland, which includes technological, economic, environmental, legal, and social directions and mechanisms to support further development and popularization of photovoltaic technology in the country. So far, no such document has been introduced at the national level. Moreover, an analysis of the dynamics of the development of the PV market and its share in the total electricity consumption in Poland is presented, as a basis for the subsequent development of the roadmap. We include in our analysis the requirement of a circular economy. The development of the roadmap is supported by detailed identification of the milestones and constraints of the photovoltaic solar energy market in Poland. We assume that such a holistic approach can contribute to the sustainable development of PV technology and the market in Poland in the next few years. This study also intends to contribute to the literature on RES, innovation, and technology development.

2. Materials and Methods

This study is divided into several specific phases. In the first phases on research, a detailed analysis of the dynamics of the development of the PV market and its share in the total electricity consumption in Poland was conducted. This analysis involved the usage of three research methods—desk research, quantitative forecasts (prediction), and comparative analysis. The desk research included revision of strategic documents and statistical databases at national, international, and European level. Moreover, industry journals and scientific publications were also searched for publications on the analyzed topic [24]. This information was supported by a critical revision of information published on the Internet and in technical energy-related reports. For this purpose, several key words were used, such as "solar energy", "photovoltaics", "PV", "renewable energy", "renewable energy sources", "RES", "roadmap", "energy". In this phase of research, quantitative forecasts were used to determine further development of the PV market in Poland, while the comparative analysis focused on the comparison of the PV market in Poland with selected European countries. The prediction and the comparative analysis were conducted based on the analysis of statistical data coming from the European Statistical Office (Eurostat) and International Renewable Energy Agency (IRENA). The time series of the percentage share of energy from PV were analyzed for Poland and two selected European countries, i.e., the Netherlands and the United Kingdom (UK). The criterion for selecting these countries for the analysis was similar insolation, i.e., comparable conditions for obtaining solar energy supplying PV panels in those three countries. Based on historical statistical data regarding the Netherlands and the United Kingdom, a forecast of changes in the share of PV energy in total electricity consumption in Poland was predicted for the next 5 years. The results of this part of research are described in Section 3.1.

In the second phase of research, a development of the PV roadmap for Poland was provided. For this purpose, technology roadmapping methodology (TRM) was used. The TRM is a versatile method of technology foresight, strategic planning, and innovation management that is used by the knowledge triangle (industry, government, and academia) with a wide range of applications, structures, and approaches [25]. The TRM is also defined as "the particular feature (and benefit) of the technology roadmapping concept is the use of a time-based structured (and often graphical) framework to develop, represent, and communicate strategic plans in terms of the coevolution and development of technology, products, and markets" [26]. One of the first scientific papers presenting TRM (and its implementation by Motorola) was published in 1987 [27]. Since that time, more than 1200 publications have referred to roadmapping, i.e., focusing on the method/tool/process as well as content of the analyzed subject matter, practical side, and development [28]. It should be underlined that roadmapping (regarding technology, product, business, or strategy planning) was developed by practitioners in industry before the first publications appeared on the subject [29]. Motorola, BP, Philips, EIRMA, Lucent Technologies, and the Semiconductor Industry Association (SIA) were among companies that have made significant contributions to the development of the TRM methodology. In these pioneering advances, Motorola used *emerging technology* and *product technology* roadmaps. Philips implemented *product-technology roadmapping* which was applied to specific systems, product range, individual projects, or components, and to production processes. The main objective of the roadmaps was to integrate the market-application-product-technology-project development interactions. Philips developed the TRM by associating it with Quality Function Deployment (QFD) tool, to transform the functional (customer) requirements into proper (technical) product characteristics [29]. The TRM is used to support management and technology planning [30] in exploring and communicating the dynamic associations between technological resources, organizational objectives, and the changing environment [26]. In the process of developing a good TRM, a collaboration between different industry branches and experts is necessary [31]. The process of TRM may be improved by using the visualization of a TRM architecture that would show surfacing issues on TRM [32]. The process of technological roadmapping can be realized in different ways [33–35], e.g., depending on the scope and method of data collection.

In the current paper, the TRM method was used for identification of both engineering and market aspects of PV technology development and dissemination in Poland. Roadmapping was used in this study since it is one of the most well-known methods of strategic planning. An interdisciplinary team consisting of specialists from the area of technology, economy, and ecology participated in establishing the PV growth conditions in Poland. The first stage of the roadmap development included an identification of PV stakeholders and determination of their expectations. The second stage of the roadmap development was literature studies that allowed the selection of the research areas and the most significant problems that were to be included in the TRM analysis. The third stage included interviews with external experts to verify and complete the previously identified research areas. The interviews were conducted with seven experts. The experts came from the following types of institutions: research institutes, universities, business associations, entrepreneurs, and managers (representing such businesses as companies installing PV, energy producers, PV components producers, investors). The fourth stage of the roadmapping involved the creation of workgroups investigating particular areas of the roadmap. Each workgroup focused on broadened literature studies as well as on the analysis of the data coming from Eurostat, literature, and other reports. This led to the proposition of the initial version of the roadmap. The research procedure is presented in Figure 1.

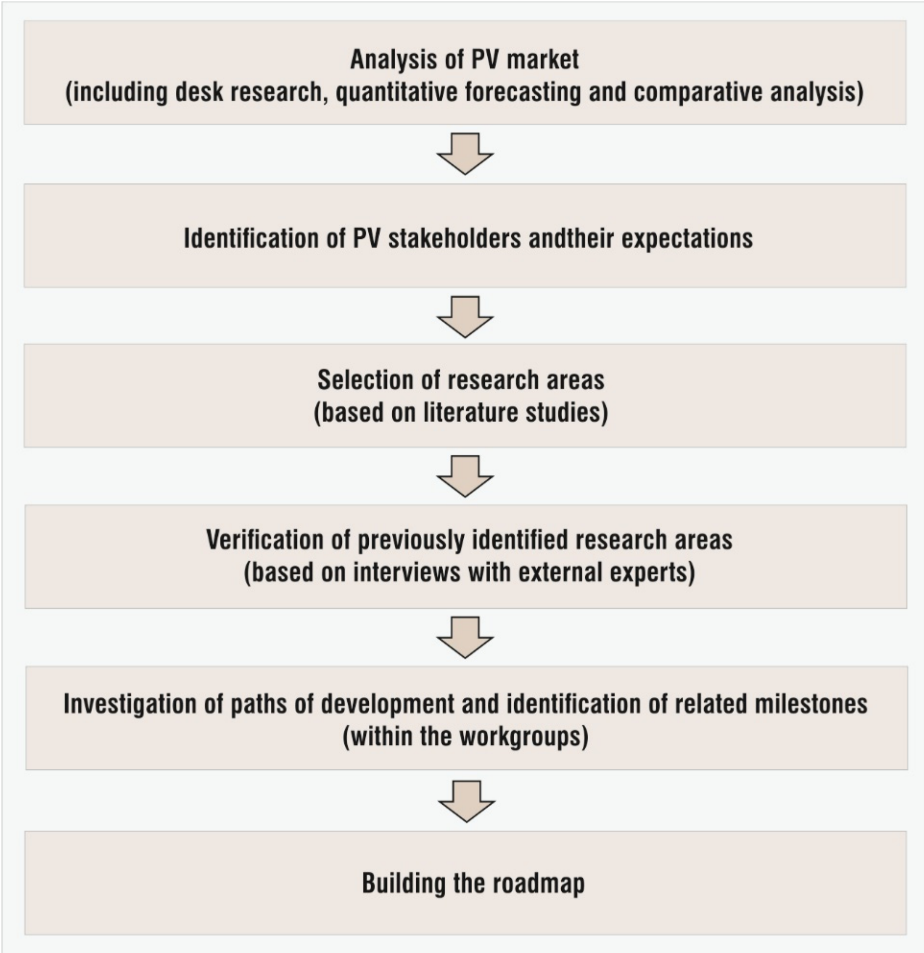

Figure 1. The research procedure.

As a result of the implementation of the TRM, the conditions which determine the development of the photovoltaic solar energy technology and the market in Poland were identified and grouped into five areas (significant importance for market development):

- Technology;
- Power grids;
- Law;
- Economic conditions;
- Social conditions.

Each of the presented categories are multidimensional and therefore comprises several developmental paths. The indicated categories and their paths were determined and described, including their milestones, potential risks, and constraints. The results of this stage of research are presented in Section 3.2. This section also provides the final version of the PV roadmap for Poland which has been established and validated as a result of the joint effort and consultation of all the research teams.

3. Results

3.1. Development of the Photovoltaic Market in Poland

Photovoltaics is a key technology for the energy transformation into decarbonized energy sources [36], which thanks to its modularity and scalability, can be used in almost all regions of the world [37]. In recent years, the PV marked has been dynamically developing thanks to the active participation of stakeholders in the whole value chain, i.e., innovators, enterprises-producers of equipment, enterprises-installers, enterprises-energy producers, administration, and prosumers [38]. An important element that should be considered in the strategic planning of energy policy in the individual countries and regions is the real potential of solar energy, which is conditioned by various geographic factors, availability of extensive unused land, and weather conditions, including insolation [39,40]. This chapter presents the dynamics of the development of the photovoltaic market and its share in the total electricity consumption in Poland and compares the situation to two other countries with similar conditions for the availability of solar light throughout the year—the Netherlands and the UK. For this purpose, the time series of the percentage share of energy from PV for these three countries were analyzed. The percentage share of PV energy in the total electricity consumption in Poland, the Netherlands and the UK is shown in Figure 2. In the Netherlands and the UK, the share of the PV energy in relation to the total energy started being noticeable in 2011–2012. During that period, this share exceeded 0.1% and began to dynamically increase in the following years. A similar situation took place in Poland in 2016–2017. To be able to compare the dynamics of the development of the PV (expressed by the studied indicator), in Figure 2 an appropriate shift in time series was made so that a noticeable significant increase in the studied indicator took place at the same time. Consequently, the year number '1' on Figure 2 represents 2009 for the Netherlands and for the UK, and 2014 for Poland, therefore the time series for Poland was shifted by five years compared to the series for the other countries. Such an assumption allowed us to predict the development of PV energy production in Poland for the following years (which is shown with a dashed line in Figure 2). For this purpose, we employed forecasting by analogy, specifically, a spatio-temporal analysis. This method assumes similarity of times series which describe the relevant economic or social processes (for example, in different countries, societies, or organizations). This method is described, among others, by Cressie and Wikle [41,42]. As mentioned before, we can assume that the process of development of PV market in Poland follows a development scheme observed before in the Netherlands and the United Kingdom.

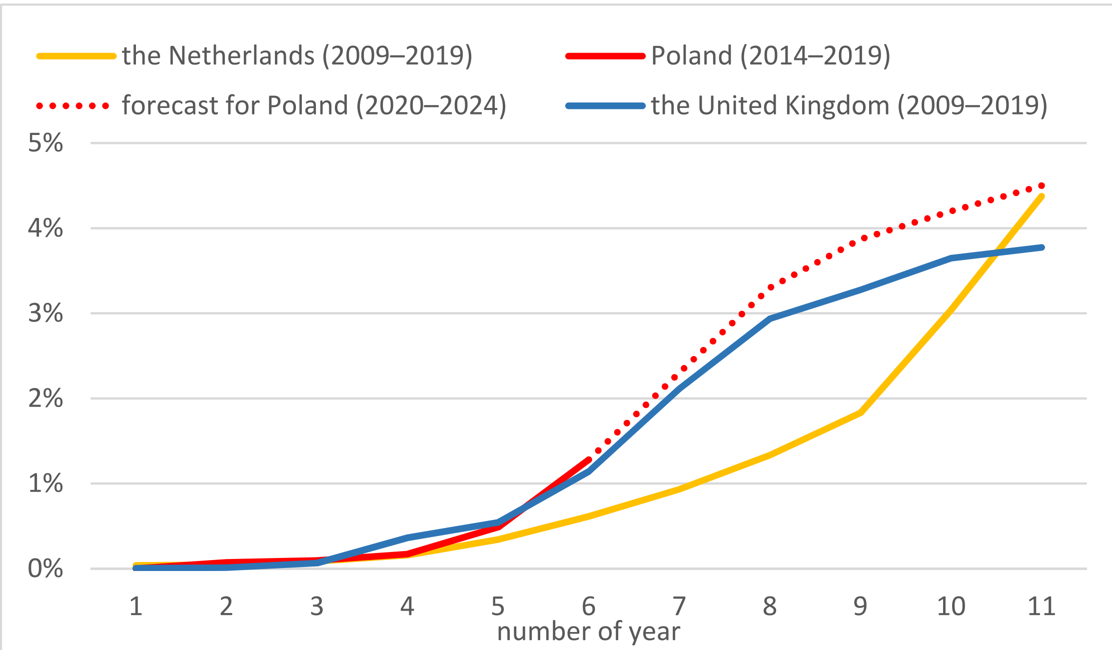

Figure 2. The share of PV energy in the total electricity consumption in Poland, the Netherlands, and the UK [own elaboration based on data from International Renewable Energy Agency (IRENA) [43], European Statistical Office (Eurostat) [44]; Energy Market Agency (ARE S.A.) [45]].

Based on Figure 2, it can be concluded that a significant difference in the dynamics of change of the analyzed indicator occurs after the third year from the adopted starting point. When analyzing the change in the indicator for Poland in relation to selected countries, one can get the impression that its PV development path in the initial phase coincides with the development path in the Netherlands. However, after the fourth year, the development of PV is gaining momentum and the curve clearly bends upwards and enters the UK development trajectory. It is also noticeable that in the case of the UK, in 2013–2016 there was an intensive development of the PV market, which contributed to the increase in the value of the PV share in total energy by about 2.5 percentage points in 4 years. In turn, later the slowdown in the growth of this indicator is noticeable and in the next 3 years it increased by less than 1 percentage point. On the other hand, in the case of the Netherlands, a more rapid increase in the analyzed indicator occurred in the last two years (i.e., in 2017–2019, when it increased by about 2.5 percent.

Currently, the dynamics of the change in the PV development index in Poland is similar to that in the UK. The development of photovoltaic energy in the UK began in 2010 when feed-in tariffs were introduced. For the first years, large-scale commercial projects dominated. This resulted in the steadily growing average capacity of the installations. This trend has only slowed down since 2017. In the following years, the increase in the number of installations is no longer accompanied by a significant increase in the accumulated installed capacity. This means that development has been propelled mainly in the segment of small home installations since 2017. Table 1 presents data that represent the development of solar photovoltaic deployment in the UK in years 2009–2021.

Table 1. Solar photovoltaics deployment in the UK in the years 2009–2021.

Year	Cumulative Capacity		Cumulative Count		Average Power	
	[GWp]	y/y [%]	[Thousand pcs.]	y/y Increment [%]	[kWp]	y/y Increment [%]
2009	0.015	-	No data	-	-	-
2010	0.096	554.1	29.9	-	3.2	
2011	0.997	943.5	235.8	687.9	4.2	32.4
2012	1.769	77.5	404.0	71.3	4.4	3.6
2013	2.888	63.2	509.9	26.2	5.7	29.3
2014	5.470	89.4	651.7	27.8	8.4	48.2
2015	9.645	76.3	840.9	29.0	11.5	36.7
2016	11.798	22.3	901.5	7.2	13.1	14.1
2017	12.690	7.6	937.5	4.0	13.5	3.4
2018	12.989	2.4	976.2	4.1	13.3	−1.7
2019	13.263	2.1	1025.0	5.0	12.9	−2.8
2020	13.435	1.3	1060.5	3.5	12.7	−2.1
Q3 2021	13.587	1.1	1103.9	4.1	12.3	−2.8

Source: own elaboration based on data from the UK Department for Business, Energy & Industrial Strategy [46].

Another country eligible for comparison (in terms of the PV market) is the Netherlands. The available data indicate that the PV market in the Netherlands has developed very unevenly in the initial phase; after the dynamic growth in 2002–2003, there was a period of stagnation (2004–2008). In 2013, the growth increased dramatically. However, in the next years, the market showed steady and sustainable growth at the level of 36–56% y/y. Table 2 presents data that represent the development of solar photovoltaic deployment in the Netherlands in years 2001–2020. In the case of the Netherlands, we have found official statistical data only on the total accumulated PV capacity up to 2020.

Table 2. Solar photovoltaics deployment in the Netherlands in the years 2001–2020.

Year	Cumulative Capacity		Year	Cumulative Capacity	
	[MWp]	y/y [%]		[MWp]	y/y [%]
2001	21	-	2011	149	65.6
2002	26	23.8	2012	287	92.6
2003	46	76.9	2013	650	126.5
2004	50	8.7	2014	1007	54.9
2005	51	2.0	2015	1526	51.5
2006	53	3.9	2016	2135	39.9
2007	54	1.9	2017	2911	36.3
2008	59	9.3	2018	4608	58.3
2009	69	16.9	2019	7226	56.8
2010	90	30.4	2020	10,950	51.5

Source: own elaboration based on data from the Statistics Netherlands (CBS) [47].

The development of photovoltaics in Poland started later than in the UK and the Netherlands. The first solar farm was built in 2011. Since then, commercial installations with a capacity below 1 MW have been mainly built. Unfortunately, there are no reliable statistics from the PV market, so we used estimates based on incomplete source data. According to our calculations, the dynamic development (y/y) in this segment did not lead to a significant increase in the installed capacity; at the end of 2016, it was only 187 MW. Legal changes introduced in 2015–2016 revived the prosumer market, which until the end of 2021 was the main driving force of the Polish PV market. The development of PV micro-installations in Poland observed in 2019–2021 is a phenomenon on a European scale. However, it can be expected that the legal changes in 2022 will significantly inhibit the development of micro-installations, while the development of farms with a capacity above 1 MW should significantly accelerate the growth of the capacity. Currently, PV energy plays important role in energy auctions in Poland. The auction in June 2021 showed a great solar performance, with more than 1.2 GW of awarded PV projects compared to about 0.3 GW allocated to wind projects. The reference price for PV was 320 PLN/MWh (69.7 EUR/MWh), and the maximum price at which the energy was sold was 243 PLN/MWh (52.9 EUR/MWh) [48]. The difference between these prices of 79 PLN/MWh (16.8 EUR/MWh) shows the high competitiveness of solar technologies and the increasing supply of large-scale solar projects. For the next auction in December 2021, it is expected that solar will take most of the 998 MW tendered capacity. The auctions for systems below 1 MW are also being dominated by solar. As a result of the last of these auctions (which also took place in June 2021), almost 1 GW of new capacity will be installed. Table 3 presents data that represent the development of solar photovoltaic deployment in Poland in years 2011–2021.

Considering the historical data for two selected countries and with the assumption that the dynamics of the PV development will be similar to that of the UK and the Netherlands, a forecast was made to change the indicator analyzed for the next 5 years (presented in Figure 2). The forecast shows that there are at least several years of dynamic development ahead of the Polish PV market.

Although the pace of the development of the photovoltaic market significantly accelerated in 2020, there are still substantial administrative and legislative barriers slowing its development. To reduce the impact of these barriers, legal, administrative, technical, tax, and other regulations should be revised to avoid the current spontaneous and chaotic development of PV systems. Our analyses show that to fully use the potential of photovoltaics in Poland, it is necessary to launch a research and development program on prospective photovoltaic cells, but above all, it is necessary to make the public aware of the possibilities of photovoltaics.

Table 3. Solar photovoltaics deployment in Poland in the years 2011–2021.

Year	Cumulative Capacity		Cumulative Count		Average Power	
	[MWp]	y/y [%]	[Thousand pcs.]	y/y Increment [%]	[kWp]	y/y Increment [%]
2011	1.11	-	No data	-	-	-
2012	1.30	17.1	No data	-	-	-
2013	2.39	84.1	No data	-	-	-
2014	27.15	1034.6	No data	-	-	-
2015	107.78	297.0	No data	-	-	-
2016	187.25	73.7	No data	-	-	-
2017	287.25	53.4	26.160	-	11.0	-
2018	565.56	96.9	52.131	99.3	10.8	−1.2
2019	1550.85	174.2	146.389	180.8	10.6	−2.3
2020	3969.76	156.0	449.348	207.0	8.8	−16.6
Q3 2021	6304.20	58.8	701.025	56.0	9.0	1.8

Source: own elaboration based on data from the Energy Market Agency (ARE S.A.) [45].

There are producers of almost all components of PV installations in Poland. The number of producers and their product offer will increase with the development of the market and the support of their R&D activities. Without the development of the Polish photovoltaic market, the chances of commercialization of innovations and the market success of Polish companies are negligible. There is a real danger that by creating conditions for the development of photovoltaic installations in Poland without adequate support for local producers in the next few years, Poland will only be a recipient of foreign technologies. Most of the production related to the components of PV systems is located in Asian countries, which in crisis situations—such as the COVID-19 pandemic—may disrupt supply chains.

It should be underlined that the PV market is related to many fields of science and industry. The use of PV requires direct interaction with other branches and technologies, such as the construction sector, distribution grids, and advanced energy storage devices [49]. On the other hand, areas of research and technology that are not directly related to photovoltaics can make a significant contribution to improving the efficiency of cells and finding new materials and production methods to increase productivity and sustainability [50]. Thus, the great advantage of the development of photovoltaic systems is the creation of jobs [51], not only in the photovoltaic sector, but also in other industries, such as optoelectronics, microelectronics, IT, and telecommunications [52]. Technological progress and market expansion are highly interdependent. Knowing the various non-technological factors that can directly affect the PV market is very important [53]. Information that can help the development of photovoltaics can be found in the following sectors: finance, law, university education, and customer incentives. Therefore, in the next section, these elements are taken into account in the assumptions for the road map for PV in Poland.

3.2. PV Technology Development Roadmap in Poland

The proposed technology development roadmap in Poland includes five key areas, important from the perspective of photovoltaic solar energy technology and market: (i) technology; (ii) power grids; (iii) law; (iv) economic conditions; and (v) social conditions. In the current section, the specific paths for further development of the PV market in each category are presented. The structure of developed roadmap of the photovoltaic solar energy technology and market development in Poland is presented in Figure 3. The specific paths include the milestones, potential risks, and constraints for the further implementation of PV systems in the country. Within each of the proposed paths, the specific milestones that must be achieved for further development are identified. The step-by-step implementation of the milestones is proposed.

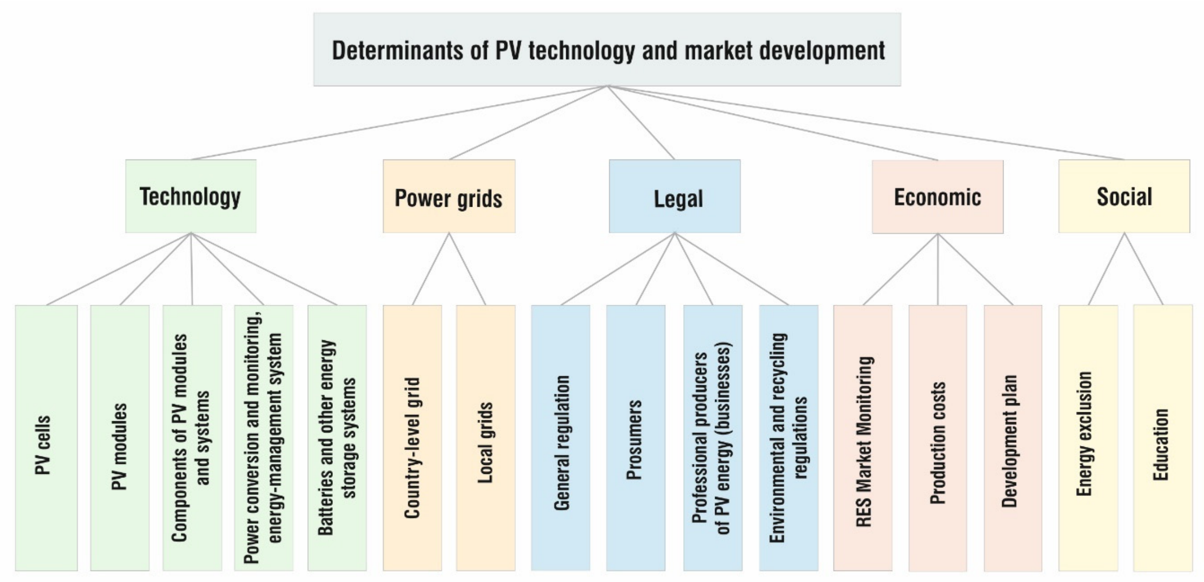

Figure 3. The structure of the roadmap of the photovoltaic solar energy technology and market development in Poland.

The detailed description of each of the proposed paths for individual areas of photovoltaic solar energy technology and market (determined in the current PV development roadmap in Poland) is presented in Sections 3.2.1–3.2.5.

3.2.1. Technology

Among the technological conditions, five main paths were distinguished:

- PV cells;
- PV modules;
- Components of PV modules and systems;
- Power conversion and monitoring and energy-management systems;
- Batteries and other energy storage systems.

Currently there is no solar cell industry in Poland except several small volume PV module manufacturers (applying imported components). There are only a few research groups in Poland involved in silicon solar cells technology on laboratory level only, BSF technology using small p-type Si wafer sizes (4″), with standard screen-printed metallization scheme allowing to achieve cell efficiencies ~17%. At present, no research and development work in the field of high-performance silicon cells are carried out in Poland and there is no production of any silicon cells. Only advanced research and implementation works are carried out on third generation (perovskite) cells. To analyze the perspectives of the development of the PV cells technology and production, three sub-technologies are distinguished in this study, namely, Crystalline Silicon solar cells (I. Generation, wafer based), along with second generation thin film cells, third generation cells and Tandem Perovskite-Si cell.

Regarding Crystalline Silicon solar cells (I. Generation, wafer based), several milestones are to be reached. It is necessary to develop a cost-efficient technology to produce PV cells which can be implemented in a short time (setting parameters: selection of the type, size, thickness of silicon substrate wafers). PERC technology seems to be a safe recommendation, which is expected to be the primary technology for the next 6–7 years. After the process of adopting the technology, concluded with the production of high-performance cells on industrial substrates (M6 or M10), the so-called “Proof of concept”, a pilot production line for the selected technology should be launched. At the same time, R&D facilities in the form of a measurement and diagnostic laboratory should be organized. Only after the successful launch and verification of the technology on the pilot line, it is advisable to start mass production, initially at the level of 300–500 MWp/year (which could be achieved not earlier than in 2024) and then gradually increase it to a capacity of at least 1 GWp/year (until the end of 2025). While increasing the production capacity, work should be carried out on an ongoing basis to optimize costs and improve the quality (efficiency) of cells. The implementation of such a plan is, however, burdened with a number of risks, including: dynamic development of technology in terms of key parameters; problems with the supply of substrate tiles (insufficient quantity, quality); insufficient quality of cells (too low efficiency, stability of parameters) and/or too high cost of cell production; problems with major degradation processes, i.e., LID or LeTID (solutions are n-type wafers or Ga doped p-type base wafers). These risks require the following actions: a flexible production line, e.g., enabling the use of different formats of substrate tiles or significant changes in the technological process; changes in the method of staging production increase; production of cells for assembly in special modules ("custom made"), e.g., of unusual shape and size, where e.g., very high efficiency of cells does not have to be a critical parameter.

The specific challenges concerning production in Poland include:

- Adoption of either of advanced cell technologies, i.e., PERC+, HJT or TopCON;
- Highly automated smart fab;
- Efficiency: 22% at first step, 24–25% goal;
- Wafers: single crystalline (preferably n-type), size: M6 first step, M10 final, occasionally M12;
- Wafer thickness: <140 µm;
- Degradation free;
- Advanced metallization schemes and technique (MBB and other techniques).

Additional challenges are:

- Optimized Si bottom cell for high efficiency tandem Perovskite-Silicon cell;
- Polysilicon, crystallization, and wafering.

We can expect a steady increase in the efficiency of PV cells and modules. The progress in this area has been monitored and reported for many years [54]. Today PERC type silicon cells are PV market horse. According to ITRPV Report from April 2021, PERC/PERL/PERT/TOPCON silicon solar cells within the next 10 years will exceed 70% market share from which TOPCon will become dominant. Monocrystalline n-type substrates should reach up to 90% of the market. Stabilized cell efficiency should approach 25–26% with a slight advantage of back contacted structures like IBC. These projections are very close to the best results in 2021. Regarding efficiency, most perspectives seem to favor Silicon/Perovskite tandem technology for which efficiency as high as 29.5% is projected in 2031 in the manufacturing process. However, today it is hard to say about LCOE competitiveness of the tandem structure with "pure" silicon technologies [55]. Following such a high pace of development is a challenge for newcomers in the market.

Due to very high investment costs and an extremely energy-consuming process, polysilicon production seems economically inviable in Poland. However, a realistic challenge would be in producing crystallization of large Si ingots, wafering with tendences toward larger and thinner wafers accomplished with continuously reduced kerf losses.

It is also worth mentioning that today there are several research teams in Poland that research thin-film PV structures classified as II. Generations, such as CdTe or CIG cells, as well as several groups dealing with DSSC or OPV cells. However, as it seems, at present there is no significant potential to start the production of PV II. Generation in Poland.

There is significant research potential to continue development and even start low volume production of Perovskite based solar cells, mainly for consumer and gadget-type applications. Regardless of the works related to the development of technology and launching the production of the I Generation silicon cells, research and implementation works on III Generation cells, mainly cells based on perovskite compounds, should be continued. To be competitive in the market, cell efficiency achieved in laboratory conditions should be about 22–24%, while in production conditions, on larger surfaces, it seems that obtaining an efficiency of 14–15% should be sufficient. A separate problem and challenge is to obtain sufficient stability and durability of the manufactured cells, confirmed by appropriate laboratories. The high attractiveness of perovskite cells/modules is related to the potentially low cost of their production combined with the possibility of using ultra-light flexible substrates. Not without significance is the very low carbon footprint (and hence a very short energy pay-back time) compared to the production of silicon cells. Therefore, the direction of further development can be outlined, starting from the continuation of research and implementation works on the III Generation cells, launching a pilot line ("proof of concept"), starting production at the level of approx. 30–50 kWp/y, to achieving production at the level of approx. 250 kWp/y and further development of technology. From a business point of view, it is advisable to search for application areas (including niche areas of application). Development of suitable Si solar cells would open a path toward highly efficient Perovskite-Si (Pero-Si) tandem solar cells being a combination of Generation I. and III. It is necessary to develop a compatible silicon cell and make a proof of concept. The production of Pero-Si cells on a pilot line at the level of approx. 30–50 kWp/y should start in the coming years, while in the following years the production of this type of cells could increase to a level above 1 MWp/year. The efficiency of this type of cells should exceed 30% (2025) to compete with the I Generation cells. However, some risks can be identified which are associated with this technology. They include too low, uncompetitive efficiency; problems with durability and upscaling; and unattractive price compared to silicon cells. The solution can be niche application areas, e.g., where the appearance, light weight, or unique functionality of the product are important.

In Poland, there are currently several small volume PV module manufacturers applying imported components, mainly solar cells, and polymeric foils. The basic characteristics of the PV modules offered by these companies are:

- Output power: 230–500 Wp, depending on cells type and module size;
- Number of cells: mostly 60, 72, or occasionally doubled for half-cut;
- Module format (cells being imported): mostly standard monofacial glass/foil configuration; occasionally half-cut, shingled or special designs for BIPV.

The total production is about 200–300 MWp/y, which is only about 10% of the PV market demand in Poland. Only one manufacturer specializes in BIPV installations and has its own, albeit limited, research facilities. Such a situation implies the need for development of own technology enabling a successful launch of production of high efficiency crystalline silicon solar cells in reasonable time and cost frames. The solution could be the adoption of one of the most advanced silicon technologies available on current PV market. An important direction requiring quick implementation seems to be undertaking research and implementation works on increasing the power and size of modules (500 + Wp and even 600 + Wp), and assembly of modules for special applications (e.g., for soundproof barriers, BIPV, floating PV). It also seems necessary to organize an accredited laboratory in Poland to certify national products for compliance with such basic standards as PN-EN 61215, PN-EN 61730. Current manufacturers should increase their production capacity to adapt production to global trends in power and module sizes and the production of double-sided modules or modules intended for special applications with specific requirements, e.g., intended for operation at increased ambient temperature, saline atmosphere or withstanding higher mechanical loads, etc., which would increase their competitiveness. The main risks associated with the production of modules are: insufficient quality (efficiency), problem with obtaining a quality and/or safety certificate (PN-EN 61215, PN-EN 61730), remaining, despite reduced, problems with major degradation processes, e.g., PID (solutions are modified cell structures, PID resistant encapsulants), excessive cost of production (EUR/Wp), and problems with the supply of components (e.g., cells or glass). An important issue is the manufacturer's warranty given to the customer. As part of risk management, solutions such as: securing the manufacturer's warranty (e.g., in the event of manufacturer's bankruptcy), linking the warranty with the manufacturer's insurance; looking for special, 'niche' yet less demanding applications markets. Other challenges associated with the development of modules technology include: the necessity of a large area, large power (500 + Wp) modules with efficiencies exceeding 21%, bifacial modules, developing highly automated smart fab, introduction of attractive power and product warranties.

Some basic module and system components are manufactured in Poland. In particular, steel and aluminium profiles are produced that are already found or can be used in the production of modules and supporting structures for PV systems. Solar glass (PV glass) and high-quality electrical cables are also produced. However, there are no connectors produced in Poland (e.g., MC4 type) which have appropriate certificates for applications in photovoltaics. To complete the supply chain, it would be necessary to start or expand the production of components in Poland—such as glass, frames, cables, or junction boxes—with the required quality certificates. As of today, it does not seem profitable and possible in the short term to invest in the production of polymer films (front- and backsheets) necessary to produce modules. However, it seems possible to produce silicone gels, e.g., to produce large-size modules for BIPV applications, and sealing materials (gels, silicone gaskets, etc.). It would certainly be advisable to develop and start the production of advanced assembly structures for PV systems, as well as to increase and develop the production of security elements for PV installations and to increase the production of cables for solar installations. All materials and components manufactured in Poland should obtain quality certificates appropriate for the area of their application. Risks include uncompetitive price, the risk of discontinuity in supply chains, and a sharp decline in demand. Considering high energy consumption costs, it is advisable to use own local renewable energy sources. In addition, it is important to diversify supply sources and shorten supply chains.

Glass production is extremely energy consuming and hence costly, with China being the world leader in glass production. China produces more glass than the country requires. European as well as US PV manufactures, though the latter to a lesser extent, are net importers of glass. Poland has a relatively strong position in glass production in Europe and, especially when considering the relative high transport costs for glass from the Far East, this may be a chance to become an important PV glass producer on the European PV market. This may additionally help lowering the barriers for new PV market entrants due to close vicinity of glass manufacturers to potential customers. Regional imbalance between demand and supply of glass that stems probably from the high diversity in cost of energy, may be helpful as well. Boosted by booming PV market resulting in growing demand for glass from PV module manufacturers, can make solar glass business very profitable. The properties of PV glass, often called solar grade glass, are different from standard glass. The PV industry needs high quality ultra-bright clear float glass for all module technologies, especially regarding module's front glass exposed to sun irradiation and ultra-bright, ironless, structured (textured), tempered glass plates with standard area up to about 3 m2 and thickness 2–3 mm, depending on size. Special requirements may be expected for glass provided for BIPV modules which must fulfil special building safety regulations. PV glass requires higher melting temperatures and extra processing steps to prevent contamination by iron particles. This causes higher investment costs required for solar grade glass production as compared to standard glass manufacturing. However, standard glass plates may be suitable for a backside for some thin-film modules and possibly also for monofacial silicon PV modules. For all others, highly transparent PV glass is essential to avoid losses on module level due to light absorption. To produce float glass, energy and raw materials make up more than 70% of the cost of goods sold. A production line for float glass requires significant investment. In addition, due to high energy consumption, access to low-cost energy is essential. Raw materials may be a barrier as well. Whereas in the case of standard glass, these are widely available silica, yet for ultra-bright PV glass, more expensive and limited resources for materials with low iron contents are needed. More than half of the world's high quality float glass is produced by four companies: Asahi, NSG Group (Pilkington), Saint Gobain, and Guardian, though for none of them solar glass is the main production issue as big companies are usually more focused on large markets of construction and automotive glass. In such situation, regarding variety of products sought by PV module manufactures, flexibility may become an advantage for smaller companies.

In the area of power conversion and monitoring and management systems, some Polish producers offer their solutions. This includes small-scale manufacturing of inverters, production of MV and HV/MV and HV transformer stations, online tools for monitoring and diagnostics of PV systems (e.g., "Onemeter", "PVmonitor"). It seems possible to increase the production level of inverters and power optimizers in Poland. It is advisable to develop the technology of inverters by adding new functionalities, such as detecting installation faults and using modern semiconductors, such as SiC, as well as popularizing the use and standardization of "smart monitoring and energy management". The obligation to use monitoring of PV installations in subsidy programs (PN-EN 61724-1) should be introduced to achieve efficiency at the level of Eff ~99%/durability 15 years. A significant risk is a failure to achieve price and quality competitiveness while a significant challenge is to ensure the protection of sensitive data and the capacity of data transmission channels. To stimulate the development of this production area, it is advisable to support research and development, expand the repair and service system, develop IT and cryptographic techniques, and build the Internet of Energy IoE (smart grid) structure and in the near future, use AI in the offered solutions. The last area refers to batteries and other energy storage systems. They represent other technology; however, energy storage technology will impact the PV technology and determine the development of the PV market. The available technologies include: Batteries Pb, Batteries Li-Ion, Batteries Ni-Cd, Batteries Red-Ox (Va), super-capacitors, super-caps. Currently, Li-Ion cells and batteries are manufactured in Poland. In the area of energy storage, the first commercial test installations are being launched. It is necessary to develop energy storage at the level of transmission and distribution networks, introduce legal solutions forcing the use of energy storage and its recycling, and develop recycling and disposal technologies, including Li-Ion batteries. Energy storage solutions carry the risk of fire and explosion of Li-Ion storage facilities due to improper O&M (handling and operation). For the development of this area of the market, the source of business risk may be the lack of demand for energy storage, limited availability and/or increase in prices of materials used in the production of energy storage (e.g., Li), environmental hazards in the event of improper disposal. It is necessary to introduce restrictive safety, fire, installation, and environmental regulations in accordance with Battery Directive No. 2006/66/EC and Directive 2013/56/EU. It is advisable to introduce legal regulations forcing the use of energy storage, develop targeted subsidies, and use alternative storage technologies.

Green hydrogen is also worth mentioning as a solution with great potential in energy storage. The first-generation installations in Poland are currently under construction, although there is no transmission infrastructure and warehouses. There is a need for development and implementation works on the production, storage, and distribution of hydrogen, increasing the production of electrolysers and hydrogen storage tanks. Subsequently, it would be possible to use the production of green hydrogen to stabilize the power grid on the basis of the DSR (demand-side response) scheme and to use green hydrogen for the development of electromobility. This technology is associated with the risk of fire and explosion; therefore, it is necessary to develop and implement safety standards and procedures. The potentially insufficient demand and development of electromobility may require the extension of application areas so that the use of this technology becomes profitable. The roadmap for the area of PV technology is presented in Figure 4.

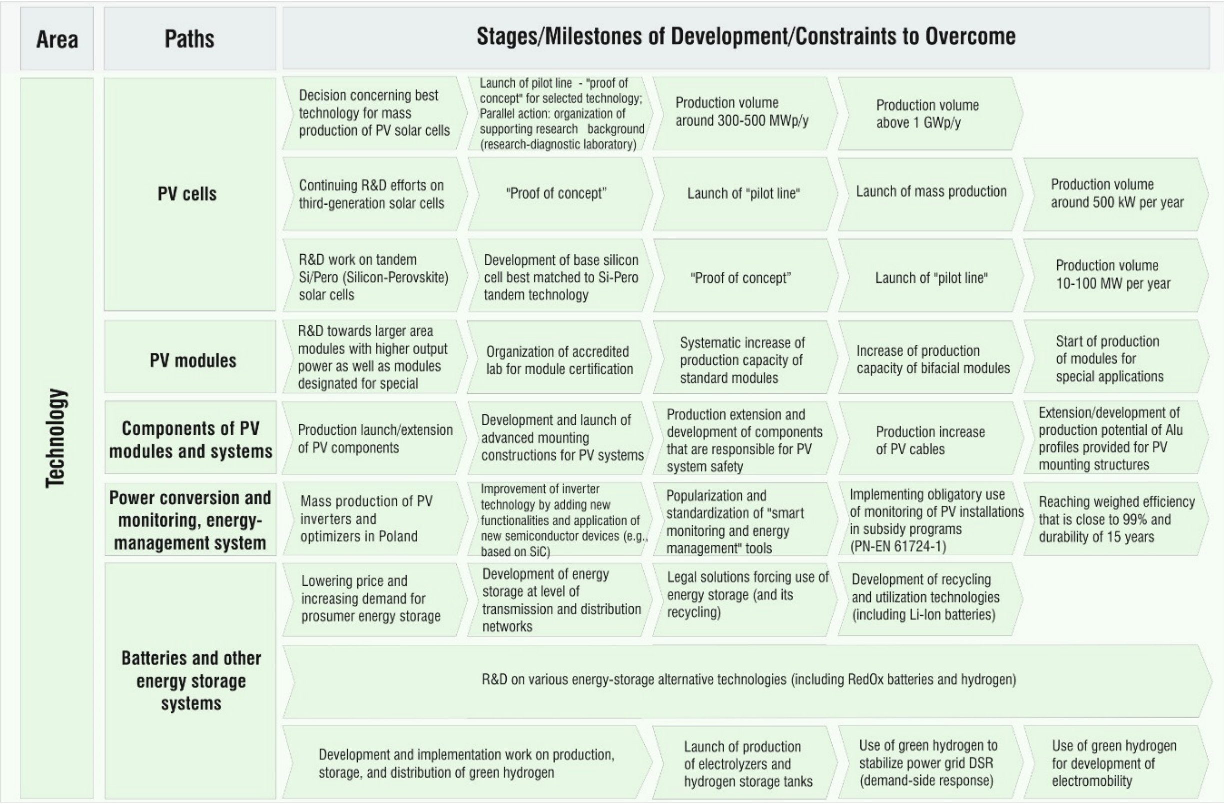

Figure 4. The roadmap of the PV technology and market development in Poland: Technology area.

3.2.2. Power Grids

The development of the PV market is strongly determined by efficiency of the power grid. The power grid needs to be developed at two levels:

- Country;
- Local.

The electricity transmission and distribution networks operating in Poland have an outdated, centralized structure. Distributed energy production in hundreds of thousands of small photovoltaic installations causes problems with the stability of these networks and limits the possibility of connecting other renewable energy sources. To ensure the proper operation of power grids, it is necessary to modernize the grid and develop utility scale energy storage systems (e.g., battery warehouses, pumped storage power plants, electrolysers) cooperating with transmission grids. In addition, it is necessary to develop IT technologies (Internet Energy—Smart Grid, production monitoring). It will be a long-term process, requiring a lot of human resources and huge financial means. The fastest action which can be taken now is the introduction of dynamic distribution tariffs, thanks to which end-users will be involved in stabilizing the operation of the grid. It is also necessary to make good use of EU aid funds for energy transformation. To avoid chaos and blackouts, all activities must be subject to detailed and forward-looking planning. In the energy industry, robotization must be introduced in the modernization and construction of new power lines. It should be noted here that the modernization of transmission networks is a costly and lengthy process, which may limit the development of the energy market, including some of the PV energy.

At the local level, there are visible limitations related to the previously binding assumptions for the development of the energy distribution network. The existing local distribution networks were designed with the assumption of a one-way flow of electricity (from the power plant to the end user). Additionally, for economic reasons it was assumed that not all end-users connected to a given network node at the same time would use the full contracted capacity they were entitled to (the so-called simultaneity factor ranging from 30–50%). In the case of photovoltaic installations, the generation of electricity in a given area is forced by weather conditions, so the simultaneity factor is 100%. Failure to adapt existing local grids leads to instability and discontinuity in energy supply. The specificity of energy generation in PV installations requires a completely new approach to the design of distribution networks (mainly low voltage), considering the high simultaneity factor. Improving the operation of distribution networks can also be achieved by creating local energy storage directly at its producers (prosumers) as well as systemically on medium voltage (MV) lines. A high number of distributed RES (in which energy generation is determined by weather conditions) connected to the grid results in the necessity to store temporary surplus energy locally. Classic battery purchase costs are quite high, and in addition, they require appropriate operating procedures to minimize the effect of aging [56]. An interesting alternative may be hydrogen technologies [57], the development of which is also slowly starting in Poland. Since the quality of the distribution networks is the main factor blocking the development of distributed photovoltaics, energy exchange should be allowed at the most local level, e.g., within energy communities and with the use of hydrogen-powered vehicles [58].

The development of photovoltaics at the local level is also limited by legal regulations forcing the distribution of energy through the public power grid. Breaking the monopoly in this area, by creating local, separate distribution networks (e.g., the new definition of "direct line") would allow for easier matching (in terms of installations with higher capacity) of local energy producers with local recipients. Local distribution networks with increased transmission capacity would also be a great support for the development of electromobility. It is also advisable to include local intelligent energy storage in the network. A major challenge will be the proper management of such local grids, ensuring the appropriate quality and continuity of energy supplies. The changes described above constitute an energy "revolution" that can be stimulated by social pressure. The roadmap for the area of power grids is presented in Figure 5.

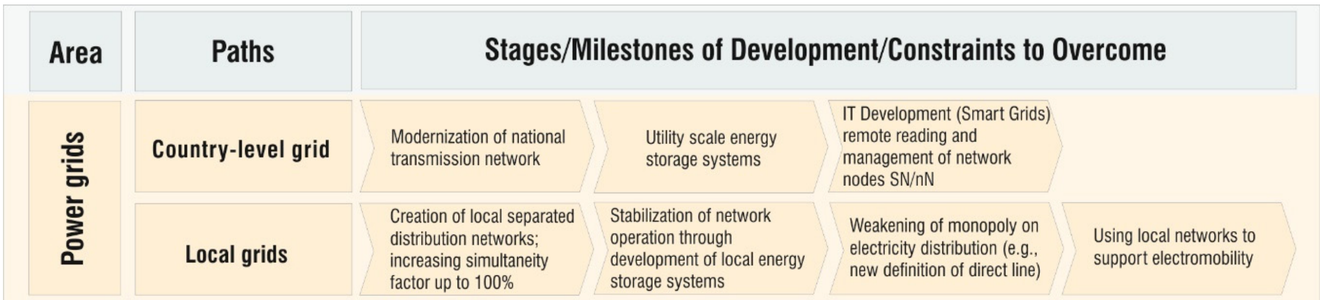

Figure 5. The roadmap of the PV technology and market development in Poland: Power grids area.

3.2.3. Law

The area of legal conditions that determine the development of photovoltaic solar energy technology in Poland includes the following:

- General regulations;
- Prosumers;
- Professional producers of PV energy (businesses);
- Environmental regulations and recycling of modules and batteries.

As a developing technology, photovoltaic solar energy technology requires new legal regulations. The intensive development of renewable energy sources, and in particular of pro-consumer PV installations, was initiated in Poland with the adoption of the Act on Renewable Energy Sources in 2015. Since then, this act has already been amended several times, sometimes completely changing the rules of the RES market. Its current form is the result of combining many legal solutions, which makes the act inconsistent and difficult to understand for an ordinary citizen. Many of the solutions it contains are ad hoc and are a response to the problems generated by the constantly changing RES market. Instability and ambiguity of regulations is a factor that hinders functioning on the market. The act should be rewritten from scratch, and the quantitative indicators appearing in it (changed with successive amendments) should be replaced with strict mathematical rules based on periodically updated (e.g., every six months) market parameters. Legislation and the language of legal acts should be simplified. Such an approach will protect the market from using too weak or too strong incentive mechanisms that could destabilize it. The act should also provide for the protection of acquired rights by guaranteeing that the new legal regulations will only apply to renewable energy installations launched after the effective date of these regulations. For installations operating before that date, it should be possible to operate in accordance with the previous regulations or voluntarily submit to new legal solutions. This is the only way to ensure the long-term and sustainable development of the RES sector, which, like the entire energy sector, requires predictable and stable legal conditions. In particular, it is necessary to clarify the legal regulations for the "power purchase agreement" (PPA and cPPA). Thanks to this approach, excessive system costs of the development of photovoltaics will be avoided, which would ultimately burden all electricity consumers. The regulations related to the safety of installations require more details (e.g., commissioning tests, fire regulations, periodic technical inspections). For example, for PV installations with a capacity above 6.5 kW, there is an obligation to coordinate their design with an expert on fire protection, and to report such installations to the State Fire Service. In this respect, the regulations also need to be detailed, because at present there is chaos in the application procedures and the appraisers have too much freedom in setting requirements and interpreting the regulations. A system of long-term insurance policies securing customers against the effects of faulty installation should also be developed.

In Poland, since mid-2019, there has been a very dynamic development of prosumer photovoltaic installations with a capacity of up to 50 kW (micro-installations). At present, their number is approaching 700,000 [40]. This was possible thanks to the simplified grid connection procedures, the "My Electricity" subsidy program and favorable rules for the way prosumers return surplus non-consumed electricity to the grid and the possibility of free consumption at other times (net metering). In the case of installations launched so far, the net metering-based system has been in operation for 15 years since its launch. Such an intensive development of PV installations does not always go hand in hand with their quality, because the price of the installation is usually the main investment factor for prosumers. In the near future, this may lead to many failures of PV installations and even to fires. Therefore, it is very important to introduce legal executive acts, ordering tests and measurements to be carried out when commissioning a PV installation, and the preparation of appropriate documentation for it. In this respect, one can rely on the PN-EN 62446 standard. Photovoltaic installations should also be subject to mandatory technical inspections, the documentation of which must be kept by their owner. New segments of the development of photovoltaics will certainly be opened by the implementation of the provisions of the EU RED II directive of 2018 into Polish law. It introduces the concepts of collective prosumer, energy communities and neighborhood electricity sales. Therefore, work on this implementation should be intensified. It also seems necessary to legally strengthen the prosumer position in the event of any disputes with DSOs and energy sellers, e.g., by introducing compensations for the forced reduction in the temporary power of photovoltaic installations. It is necessary to develop independent audit firms that can participate in resolving disputes. A matter that seems distant but will certainly affect the development of the prosumer segment, is the regulation of the method of balancing the energy supplied to the grid after the 15-year period of the discount system. Work on the relevant regulations is currently underway. The proposed solution must be financially neutral and must not generate additional administrative obligations on the part of prosumers. It seems that the simplest and most appropriate method will be to continue to use net-metering, with possible changes to the detailed rules.

Photovoltaic installations with a capacity of over 50 kW are developing much worse in Poland than prosumer installations. This is mainly due to the lack of appropriate regulations. While the share system for selling energy from photovoltaics is quite well solved, entrepreneurs who do not want to sell energy generated in photovoltaics but want to use it for their own needs have been forgotten. With installations up to 50 kW, the entrepreneur can be a prosumer using the balancing under the discount system or selling unused surplus energy. However, usually 50 kW is too little power to significantly balance the energy needs of such entrepreneurs. With higher capacities, problems with the construction of the installation begin (full construction procedure with a building permit), problems with connecting to the network (issuing connection conditions) and the lack of simple possibilities to sell surplus unused energy. To activate the development of this market segment, similar construction simplifications and energy balancing should be introduced for small PV installations (up to 50 kW) as for micro-installations (up to 50 kW). The aforementioned legal changes in the field of separate distribution networks and a direct line would certainly facilitate the sale of photovoltaic energy to industrial customers based on PPA and cPPA contracts. Observing the RES energy auctions, it can be said that in recent years, photovoltaics has had a significant share in them. However, it should be remembered that the validity of the rules on auctions ends in 2021, and the European Commission has not yet approved the plans to extend this period. In order to ensure further development of PV installations with capacities above 1 MW, energy auctions must be planned for the next few years. It is also worth creating a separate technological basket for photovoltaics, because now it must compete in terms of price with wind energy on land. The effect of this competition so far has been such that only photovoltaics has won in auctions for systems with a capacity of up to 1 MW, and wind turbines have won the auctions for systems above 1 MW. Therefore, it is difficult to discuss sustainable development here. It is necessary to launch various mechanisms ensuring the sustainable (stable) development of the market.

While the photovoltaic system does not generate any harmful emissions to the environment during normal operation, the photovoltaic system must be recycled after its operational period (25–30 years). It seems a distant prospect, but some elements of PV systems (e.g., batteries, inverters) require prior recycling. Additionally, the first commercial PV installations built in Western Europe at the end of the 20th century are already being decommissioned. To avoid the import of huge amounts of electro-waste to Poland, very strict legal and procedural supervision over this activity should be introduced, related to the EU environmental directive. By recycling photovoltaic systems, mainly aluminum, glass, silver, and copper can be recovered. Recycling procedures for silicon modules are well known, but for CIS/CIGS and CdTe modules, much research and development is still required. The same is the case with rechargeable batteries. Procedures for lead-acid batteries have been refined in the automotive industry, but Li-Ion batteries are a novelty that requires a completely different approach, if only because of the risk of fire. It is worth considering that most of the elements of photovoltaic systems may be repowering instead of recycling. After minor servicing works, such elements can get a “second life” in line with the philosophy of the circular economy. Appropriate legal regulations can force producers of photovoltaic system components (e.g., inverters) to have a modular structure that facilitates repairs, and the obligation to provide technical support throughout the expected period of operation of the PV system (about 30 years). Therefore, regulations should be introduced to ensure the reduction of the level of electro-voltage from PV installations and the safety of their disposal. Activities in this area should be in line with WEEE Directive 2012/19 EU. The roadmap for the area of legal regulations is presented in Figure 6.

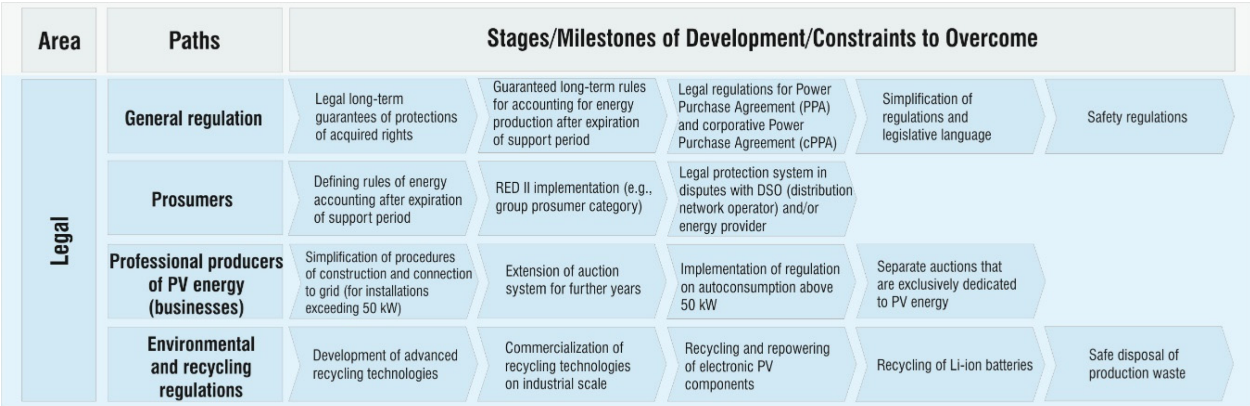

Figure 6. The roadmap of the PV technology and market development in Poland: Legal area.

3.2.4. Economic Conditions

In the area of economic factors that determine the development of photovoltaic solar energy technology in Poland, three paths have been identified:

- Capital investments;
- RES market monitoring;
- Production costs;
- Market development planning.

Electricity produced from photovoltaics in Poland has not yet reached grid parity, therefore its development must be stimulated by various subsidy programs. For these programs to be effective and not generate excessive costs, it is necessary to constantly adjust them to the changing market realities. For this one would need up-to-date data on the installed power and the amount of energy produced in photovoltaic systems. At present, there is no consistent and reliable information on this matter in Poland. Many institutions prepare their own statistics, which sometimes vary greatly. There is an urgent need to create uniform, publicly available information registers, in which data on the development of the photovoltaic market would be constantly updated. It is worth introducing a unified and, if possible, automated system for reporting the operation of photovoltaic systems. The obligation of such reporting should, by virtue of law, apply to all installations built with the support of public funds. However, it should be remembered that data on production, and even more so on electricity consumption, are sensitive personal data and must be adequately protected in accordance with the GDPR procedures. It seems sufficient to anonymize these data before making them public. With the current information chaos, it is difficult to effectively manage the development of the RES market. If the aforementioned public registers existed, it could be possible to introduce automatic management of subsidy programs, which would be predictable and transparent for investors.

Sustainable development of photovoltaics should—through the economies of scale—lead to a significant reduction in investment costs in the near future. However, care should be taken that this development is not slowed down by excessive operating costs, such as distribution fees and taxes.

Until the solar farm reaches grid parity, subsidy programs and tax breaks will be necessary, designed in such a way as not to translate into an uncontrolled increase in electricity prices. It is necessary to regularly set new quantitative targets for PV capacity for each subsequent year, considering long-term targets formulated at the EU level. After obtaining the grid parity, the systemic protection should continue to cover prosumer photovoltaic micro-installations, because their functioning is far from the rules of the free energy market (the instruments relating to this have been previously indicated in the legal factors, under the path prosumer). Moreover, it is advisable to introduce subsidy programs for energy storage and hybrid installations. A factor supporting the supply side would be a support program for the domestic production of PV components and investments in research and technological development (at the level of at least 5% of the sales value of PV component producers). A threat to stable development may be the dynamic increase in energy prices. In addition, there is a risk of a sharp change in the state's policy in the field of renewable energy (and PV in particular) and discouragement of investors. It is necessary to establish a stable, long-term policy conducive to the development of renewable energy sources. The roadmap for the area of economic conditions is presented in Figure 7.

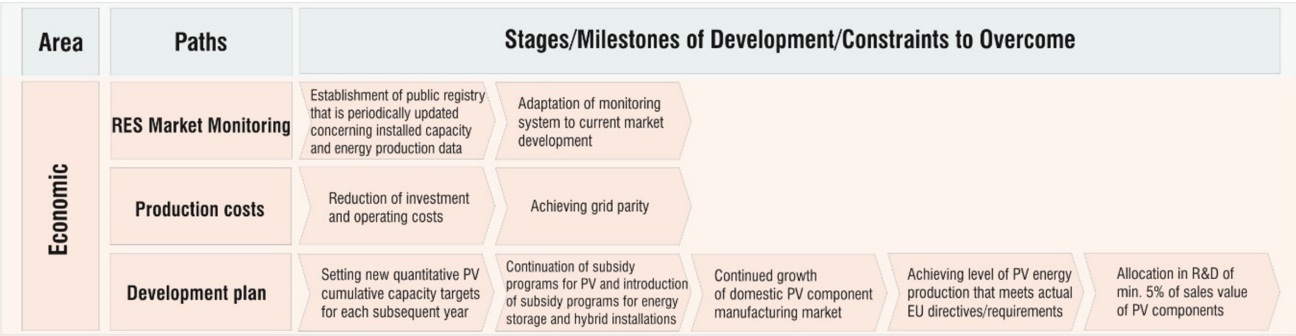

Figure 7. The roadmap of the PV technology and market development in Poland: Economic area.

3.2.5. Social Conditions

Among the social conditions that determine the development of photovoltaic solar energy technology in Poland are the following:

- Energy exclusion;
- Education.

The development of photovoltaic technology has a positive social impact; however, some milestones need to be achieved. The energy transformation, an element of which is the widespread use of photovoltaics, in addition to the technical and economic dimensions, also has a very important social dimension. Social acceptance of this transformation and the consent to bear the additional costs associated with it increases significantly with the awareness that every citizen can participate in it. So far, PV installations are so expensive that only wealthy people can afford them without subsidies. In a society where currently about 10% of the population is affected by energy poverty, this phenomenon may worsen as a result of the energy transformation. Social welfare programs can alleviate this process to some extent. However, a more effective solution will be to create a secondary market for low-cost solar PV systems. Elements of PV systems appearing on this market may come from, for example, repowering, with the obvious observance and control of quality and safety procedures. It is also worth introducing the provisions proposed by the RED II directive, according to which the prosumer does not have to be the owner of his photovoltaic installation. This will allow less-wealthy people to share their own space (roof of the building, plot) with external entities for the construction of a PV installation, in exchange for the possibility of using part of the energy produced by them free of charge. Due to the risk of worsening energy poverty, it is advisable to develop a system of financial protection for the poorest.

Social acceptance of a photovoltaic battery largely depends on the level of knowledge about this branch of energy. Meanwhile, the level of environmental, technical, and economic knowledge related to PV varies. There is no reliable information about the real costs of the energy transformation. As a result, the society is susceptible to manipulations, blaming photovoltaics (as the most dynamically developing renewable energy sources) for the inevitable increase in electricity prices on the retail market and the destabilization of power grids. Introducing PV topics at every stage of education (from elementary school to university), thoughtful campaigns in traditional and electronic media, and consolidating the activities of many PV industry organizations can significantly improve the public perception of PV. It is important that the information provided is not of a marketing nature.

They must be reliable, showing the advantages and disadvantages of photovoltaics and pointing to the risks posed by improperly made, low-quality PV systems. The roadmap for the area of social conditions is presented in Figure 8.

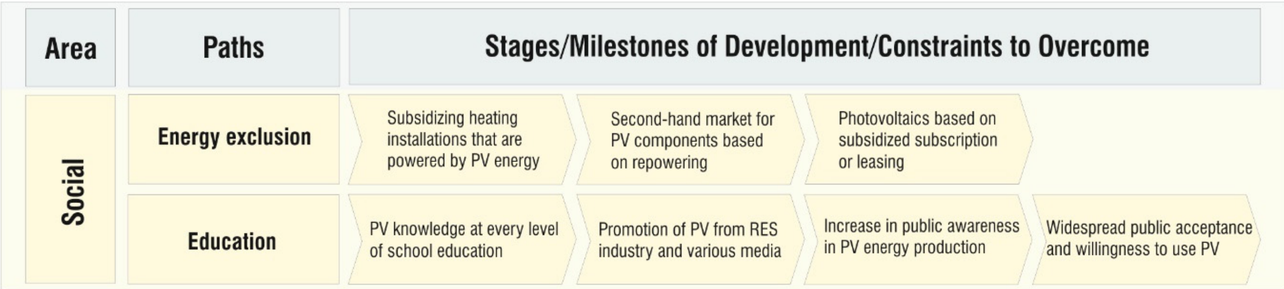

Figure 8. The roadmap of the PV technology and market development in Poland: Social area.

4. Discussion

The roadmap presented in Figures 3–8 gathers engineering factors together with others (in our case, legal, economic, and social). It is an advantage of this analysis compared with other studies which focus on selected issues. This holistic approach enables us to identify the associations among different areas and paths of technology and market development. For example, this analysis emphasizes the significance of balancing the development of production infrastructure (which is stimulated with public subsidies for prosumers) with the development of the power grid (mainly on a local level). This shows the interdependence between economic and infrastructure areas. The other example of challenges is the lack of legal regulations regarding the recycling of the panels in the future. This challenge refers to the technological, legal, and economic as well as social areas in parallel.

This study contributes to the implementation of the process of transformation toward decarbonization of the energy system, clean energy supply, and climate neutrality which are posited in the EU strategy (e.g., [1,2,8]), in particular to the development of alternative energy production solutions and renewable energy systems (RES) [4]. The proposed roadmap contributes to the long term goals at the national level by identifying determinants of the PV market and technology development specific for Poland. As Poland has an important share in electricity consumption and generating electricity based on hard coal, this analysis can play a significant role regarding the EU goals (e.g., EGD) as well. The proposed roadmap along with the projection of PV market growth can help to plan and regulate the further development which is growing up dynamically currently.

The presented investigation confirms that the PV market is related to many industries, as is reported in the literature [49]. Consequently, the economic conditions and legal regulations in the associated sectors (e.g., the construction sector) impact the development of the PV sector. The identified steps of development confirm the fast pace of development in the area of cells, materials, and production methods, as well as uncertainty regarding future directions of development indicated in the literature [50].

Additionally, this study contributes to the methodology of technology roadmapping through its implementation in the new subject and geographical context. This study confirms, that TRM is a useful tool that offers an opportunity to explore a wide range of factors determining the development of technology and the market.

5. Research Limitations and Future Prospects

This study has some limitations. Despite the high number of identified determinants representing different areas, some other factors were omitted. They include, for example, political factors (mainly country-level politics), changes in energy price, and challenges for global logistic chains (like these sourced in lockdowns). This study reflects the opinions of experts representing different groups of stakeholders; however, these opinions are not fully balanced (as a panel was not fully balanced due to limited accessibility of experts). This can result in overstressing some aspects, while others can be undervalued. This study uses the technology roadmapping methodology. The identified factors can be grouped in different ways what would result in other structures of the roadmap. For example, the environmental factors may constitute the separated area (in our case it is included in legal factors). The photovoltaic market and technology are under ongoing development, especially engineering solutions and the legal environment changes dynamically. Thus, the proposed roadmap will require updating on a regular basis. In the case of this study, TRM enabled to set numerous factors together, however, these factors are not analysed in depth; to understand them to a greater degree, it can be necessary to search for other publications which focus on particular factors. Finally, this study examines determinants of PV technology and market in one country (Poland). Some of the identified factors are universal and they are significant in other countries, however not necessarily to the same degree. Some other factors are specific for Poland and in other locations or legal systems may not be relevant (for example subsidy system or solar conditions).

The developed roadmap indicates main drivers and barriers for photovoltaic market in Poland. It suggests that photovoltaics may have a significant contribution to the development of the energy systems, which should be based on renewable energy sources, and which are indicated as the key directions of the strategies for the development of the country [11] and the EU [1]. It is emphasized that making photovoltaics is a key component of a sustainable energy system—cheap, decentralized, safe, and environmentally friendly. This requires certain key actions to be initiated and carried out over the next decade. The key factors of the success in this area are integrated initiatives and actions that should be implemented by different stakeholders of the PV market—industrial bodies and public market regulators, politicians, scientists, and other key groups of entities from various fields (including shareholders in all other types of renewable energy, as well as grid operators, energy suppliers and power plants).

Further market development requires the PV energy market stakeholders to focus on three main areas of activity:

- Support and direct the development of renewable energies—the aim is to enable, through the use of support mechanisms, a stable increase in the number of PV installations to obtain the potential of min. 15 GW in 2030. The development of PV systems must be oriented in such a way as to enable their connection to the grid and integration with the energy system. In addition, the product-based nature of photovoltaics—for example the provision of grid services—should be further developed through a system of appropriate incentives and thus integrated into the energy market;
- Strive for the integration of photovoltaics and other types of renewable energy into the energy system—the development of photovoltaics and other types of renewable energy is transforming the energy system from the centralized one that still exists to the decentralized one. So far, the network is being built for a centralized system. The growing number of connections of new renewable energy producers with variable production dynamics, who do not operate within the central system, poses new challenges that require adaptation of the distribution system;
- Develop and make available the necessary technology—to achieve rapid progress in activities indicated above, and to reduce conversion costs. This, in turn, requires research and technological development to be undertaken.

The proposed recommendations have strategic importance for both managers and policymakers representing different groups of stakeholders. Rapid growth and the upcoming transformation of the energy system to a 100% renewable energy system pose new challenges for the Polish industry. The PV sector, with its strategy, goals, and action program, has created the basis for its own contribution to the upcoming system changes. In the coming months, a very important task shall be to initiate consultations with other stakeholders to develop specific implementation plans for individual actions.

The sustainable energy system requires involvement of a wide range of stakeholders in the whole value chain of the PV sector. Each stakeholder must perform their part of the work while ensuring that photovoltaics is in the right status as the industry of the future. Currently, the participants of the energy supply market have different positions on the development and support of renewable energies. In particular, the market position of "classic" energy suppliers and producers is threatened by the development of a decentralized system of solar power plants. Conventional power plants will also become less productive due to shorter operating times. However, at least in the medium term, conventional energy cannot be excluded, especially in terms of market balancing. Constructive dialogue between partners is therefore essential in order to overcome these mounting challenges.

The implementation of the actions planned in the developed roadmap will contribute to the transformation of the Polish energy system into a more sustainable and compliant system, facilitating EU requirements. In addition, the presented aspects of the PV market in Poland and the indicated paths may be used by policymakers to further implement legal regulations and initiatives for the development of photovoltaics in Poland (such as further promotion of the "My Electricity" program), and can be used by entrepreneurs in entire value chains for planning further PV solutions.

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