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IMPACT OF PHOTOVOLTAICS DEVELOPMENT ON ELECTRICITY GRIDS – POSSIBLE SCENARIOS ON THE EXAMPLE OF POLAND AND GERMANY

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Purpose: The purpose of the article is to analyze the reduction of PV generation in Germany and Poland and possible ways to solve it.
Design/methodology/approach: The analysis was conducted using available secondary data and literature. The study's time scope is from Q1 2013 to Q1 2024.
Findings: The answer to the challenges is the continuous modernization of the power grid towards smart grids. A necessary element is increasing the flexibility of the power system through the development of energy storage and new grid services.
Research limitations/implications: Limitations apply to the Polish and German markets.
Practical implications: Based on the analysis of the Polish and German markets, the authors proposed possible scenarios for the development of PV networks and possible actions aimed at continuous modernization of the power grid towards smart grids by conducting programs to support the development of national network infrastructure.
Social implications: Reducing the negative impact on the environment and identifying opportunities to build smart grids.
Originality/value: Few studies have examined the effects of integrating RES into power grids. The research gap detailed the analysis of grid deactivation cases in Poland and Germany. The two markets were compared due to their geographical proximity and their significant differences.

Keywords: PV shutdown, grid forming, re-dispatch, Smart Grid, non-market reductions.
Category of the paper: Research paper; Viewpoint.

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1. Introduction

In recent years, we have seen rapid photovoltaic (PV) growth in Europe, including Poland. The total installed PV capacity in Europe at the end of 2023 was 263 GW, and available scenarios forecast further growth. With the rapid growth of PV, there are side effects that are increasingly visible and felt by PV market participants. More broadly, PV systems and RES technologies significantly affect the reliability and quality of power supply because they are stochastic, uncontrolled, variable and primarily unpredictable. In addition, most of the commonly favored RES technologies do not provide inertial support, making the grid vulnerable to failures. Meeting these challenges requires additional auxiliary support systems and, more importantly, monitoring and communication networks. The current grid needs to be modernized in various operational aspects related to the network, from generation, transmission (Vita et al., 2016; Adewumi et al., 2022; Zafeiropoulou et al., 2022) and distribution, including operations, to power system planning. The above efforts are aimed at preserving the flexibility of the grid, including transformation and diversification (Ahmed et al., 2023; Ahmed et al., 2022; Salman et al., 2021) towards facilitating RES integration.

The modern electricity grid around the world has evolved over the past decades. It delivers electricity from a central generating unit through transformers and various levels of the transmission grid. In Poland, the electricity grid was mainly based on conventional coal-fired electrons. The rated capacity of such central generating units reaches thousands of megawatts (MW). The largest conventional power plant in Europe is 5102 MW in Belchatow. Conventional generating units are connected to the transmission grid with a good communication framework. This allows the power system to operate acceptably with sufficient security and reliability while maintaining a coordinated energy market (Kabalci, 2016). The distribution network built to serve central generating units has a high level of complexity but a relatively small number of integrated communication links. This makes it difficult to use modern distribution network control technologies at the local level. On the other hand, existing communication links mostly lack real-time monitoring to regulate the power quality of large loads realistically.

Modern technological advances in communication systems allow for much more monitoring and coordination. This, in turn, allows for better network monitoring, controllability, and flexibility while lowering operating costs, which aligns with the modern trend of RES integration.

Therefore, the concept of creating a Smart Grid (SG) provides an opportunity to implement information and communication technologies (ICT) to modernize the power grid system (Anjana, Shaji, 2018). However, the large-scale network of current power systems imposes the need to establish an optimized SG, which is justified given the network's multifaceted requirements in terms of communication, sustainability, interoperability and power quality in order to maintain the technical and economic importance of the entire network (José de Castro Vieira, Tapia Carpio, 2020).

At the same time, the current transformation towards decarbonization to protect the environment requires the inclusion of RES in building a sustainable power system and meeting the ever-increasing demand for electricity. This transformation of the power system on the generation side requires a higher degree of communication networks to maintain grid integrity (Moslehi, Kumar, 2010). Most current RES technologies depend highly on topography and the environment, making them unpredictable and uncontrollable. This consequently limits their large-scale integration into electricity grids. In addition, this requires appropriate demand management and innovative strategies in renewable energy integration (Hossain et al., 2016). Modern grid control services, power electronic converters, smart meters and smart inverters require a state-of-the-art communications network (Phuangpornpitak, Tia, 2013). Therefore, creating an effective smart grid provides viable load management, significant reductions in system losses, reduced energy waste, accurate data monitoring, and flexibility for expansion and integration into the power system grid.

Similarly, SG consists of unidirectional communications, centralized generation, limited sensors, manual controls, and maintenance, which provides limited opportunities for customers to participate. A systematic change in the direction of SG development is being observed around the world, with simultaneous intensive innovations in each domain of SG considering their respective challenges (Lund et al., 2017; Alvi et al., 2022; Faheem et al., 2018; Ketter et al., 2018; Khan et al., 2023). Challenges facing European electricity grids due to the development of RES include the need to deliver flexibility, resilience and reliability to enable diversification and transformation while maintaining quality, stability and energy flow.

One of the new challenges in Europe related to the emergence of RES on the power grid is the emerging shutdown of PV installations by distribution grid operators on behalf of the national grid operator, known as non-market reduction of PV generation. These challenges are faced by countries where the share of RES in the national power system is increasing.

There are few studies on the effects of integrating RES into power grids. In contrast, there needs to be more scientific reports on the non-market reduction in the generation of photovoltaic sources due to their integration with electricity grids. Consequently, the research gap detailed the analysis of grid deactivation cases in Poland and Germany. A comparison was made between the two markets, on the one hand, due to the geographical proximity of the two countries and, on the other hand, due to the significant differences the two countries share. The German market is a mature and largest RES market in Europe with different legal, economic and technical conditions. On the other hand, the Polish photovoltaic market is still developing.

This article aims to analyze the reduction of PV generation in Germany and Poland and possible ways to solve it. The analysis was conducted using available secondary data and literature.

The research's time scope is from Q1 2013 to Q1 2024. The research methodology assumes that secondary data from Eurostat and other available statistical materials will be used.

2. Development of photovoltaic installations in EU countries

In 2023, installed solar capacity in the EU-27 member states increased by 27%, reaching 263 GW compared to 2022, when it was 207 GW (Solar Power Europe, 2023). After PV capacity in the European Union surpassed 100 GW in 2018 and reached the so-called 200 GW milestone in 2022, the upward trend was thus confirmed (Figure 1).

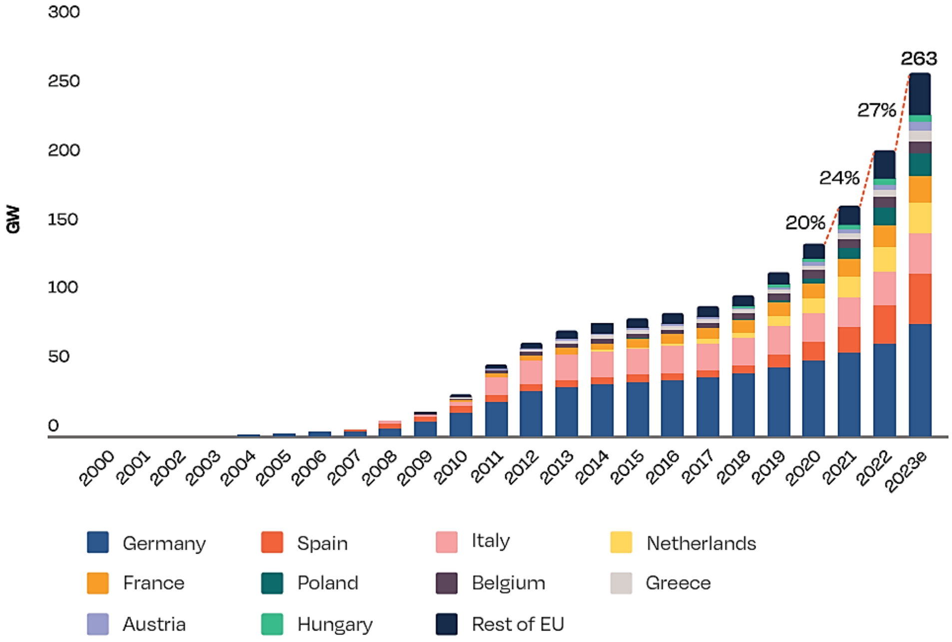

Figure 1. Cumulative solar PV installed capacity 2000-2023.

Source: (Solar Power Europe, 2023).

Against European countries' background, Poland's PV industry in 2019-2022 was characterized by significant dynamics. The total installed PV capacity in the EU at the end of 2022 was 198 GW, with an increase of 36 GW of new PV installations, an increase of 22% compared to 2021. From 2019 to 2022, Poland was among the top countries with increased PV capacity (Table 1). At the end of January 2024, Poland's total installed PV capacity was 17.07 GW.

Table 1.
Total installed capacity in selected EU countries in 2022.

Country	Total power 2021 [GW]	Total power 2022 [GW]	Increase 2022 [GW]	Average Increase [%]
Germany	59.371	66.662	7.291	12
Italy	22.594	25.077	2.483	11
Holland	14.911	18.849	3.938	26
Spain	13.715	18.214	4.499	33
France	14.810	17.410	2.600	18
Poland	7.416	12.422	5.006	68

Source: (IRENA, 2022).

However, Germany is the EU's largest and most mature PV market. Currently, Germany is the largest PV operator in the EU, with 82.1 GW of installed capacity. The country's rapid continuous growth of PV in recent years has widened the gap with Spain, second in this classification, with 35.6 GW of installed capacity. Analyzing the combined shares of the leading solar markets in the EU, Germany has slightly lost market share by two percentage points to 31% of the European market share, which still accounts for almost a third of the total installed PV capacity in the EU. Poland's share in the EU is 6.4% and has proliferated in recent years. Total installed PV capacity projections for the EU covering 2024-2027 show double-digit annual growth rates (Figure 2).

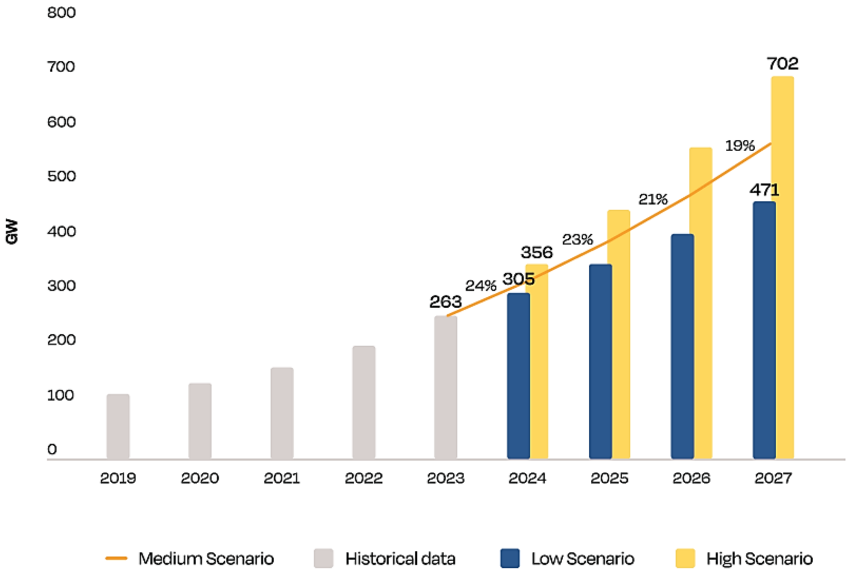

Figure 2. Scenarios for PV capacity growth in EU countries.

Source: (Solar Power Europe, 2023).

In the medium scenario, total capacity will reach growth rates of 24% in 2024 and 23% in 2025. According to Solar Power Europe experts, as PV grows in the EU, annual percentage growth will decrease significantly due to market saturation. The medium scenario predicts relative growth rates of up to 21% in 2026 and 19% in 2027. Thus, the upcoming growth rates will be lower than those achieved during Europe's 2022-2023 boom, when gains reached 24% and 27%, respectively. Regardless of the scenario, experts forecast further growth in

PV installation capacity in EU countries. Therefore, responding to the emerging side effects of such dynamic PV development is essential.

3. Challenges of power grid development in the context of RES developments

The development of RES raises entirely new challenges for the electricity grid. The fluctuations in the integration of RES into the traditional power grid make it challenging to use renewables at the transmission level, which must handle the full range of rapidly fluctuating energy sources (Howlader et al., 2016; Cheung et al., 2010). This hinders the integration of RES into the electricity grid and vice versa, affecting the urgent global demand for a sustainable energy sector. The operational limitations of the power system are mainly due to the voltage and frequency limits set for the power system. Network insulation is damaged, leading to short circuits and equipment failures with system tripping due to overvoltage and undervoltage, respectively. These challenges have been mitigated by interconnection over a wide area at the national and international levels and solved with voltage regulation devices (Vaccaro et al., 2011; Andreotti et al., 2019).

Similarly, a slight deviation in system frequency causes desynchronization. Frequency stability is mainly maintained using automatic generation control (AGC) strategies. Offloading strategies are also recommended in emergencies.

Thus, given the dynamics of RES, which undergo unpredictable output power fluctuations, fast-response control strategies are needed. Unfortunately, most conventionally developed solutions are proving ineffective (Jamroen, Dechanupapritta, 2019; Lam et al., 2016; Keyhani, Chatterjee, 2012).

Based on the solutions presented for RES integration, it is mainly recommended that the forecasting of RES power production and the availability of energy storage systems be combined to increase the reliability and flexibility of the power system and maintain the techno-economic viability of the entire operation. However, most of these solutions require power system upgrades in the form of state-of-the-art communications for data acquisition, processing and optimization.

Electricity use has now been integrated into many critical areas and human welfare, classified as essential loads. Ensuring a reliable and safe power supply to these loads is necessary, and safety has been achieved by designing redundant circuits. In this perspective, establishing smart grids provides a structure that enables post-failure detection algorithms to use each power grid component optimally, thus eliminating the need for redundant circuits. As such, establishing a smart grid provides a transition from conventional grids to a modernized grid that facilitates collaboration and responsive interactions (Mahdad, Srairi, 2015).

It also encourages introducing prosumer systems into the energy sector, allowing two-way interaction. This is integral to the creation of a deregulated electricity grid, which is necessary due to the constraints and demands that current RES technologies bring.

What is more, the activation of high-quality two-way communication in smart grids allows the incorporation of a complex, intelligent algorithm that enhances the reliability and self-repair capability of the power grid. Modern electricity sectors are being encouraged worldwide to move to smart grids. As the power grid slowly moves from a centralized architecture to a decentralized one, many new technologies are being proposed to support the systematic decentralization of the smart grid's communications and information infrastructure. These technologies are based on new and standard models successfully applied in other industries (Maddikunta et al., 2022).

Due to wind and solar power's uncontrollability, limited dispatch ability, and intermittent nature, dedicated ancillary services, such as regulation services, are needed to ensure reliability and operational needs.

One of the main reasons for RES integration is the potential rapid change in generated output. This, combined with the existing variability of this load, increases the stochastic nature of the entire power grid. RES at both the generation and distribution levels requires a coordinated power system upgrade for detailed monitoring, control and regulation. In particular, the current distribution level will require monitoring and control upgrades to optimize reliability and security and ensure the flexible operation of diverse RES-based small-scale generation systems (Manditereza, Bansal, 2016). The main idea is to optimize flow and power quality while reducing stochastic complexity.

While the existing power grid is adapted to cope with load variability, the available support provided by conventional power systems needs to be improved with the development of RES. Therefore, replacing or converting the output of synchronous generators will require systematic grid reinforcement, considering the variability of the time scale, i.e., the rapid fluctuations of renewable energy sources. Accurate wind and solar power forecasts are required to enable the specific tasks and additional services placed on RES generation sources. In addition to the generation forecast, local scheduling procedures for resources with unpredictable production characteristics must be refined to accommodate energy market requirements (Lee et al., 2022). The above elements should be taken into account when planning RES investments. Typical aspects of RES investment planning related to connecting new generation capacity to the electricity grid should consider power quality, contingencies and other necessary investment elements (Figure 3).

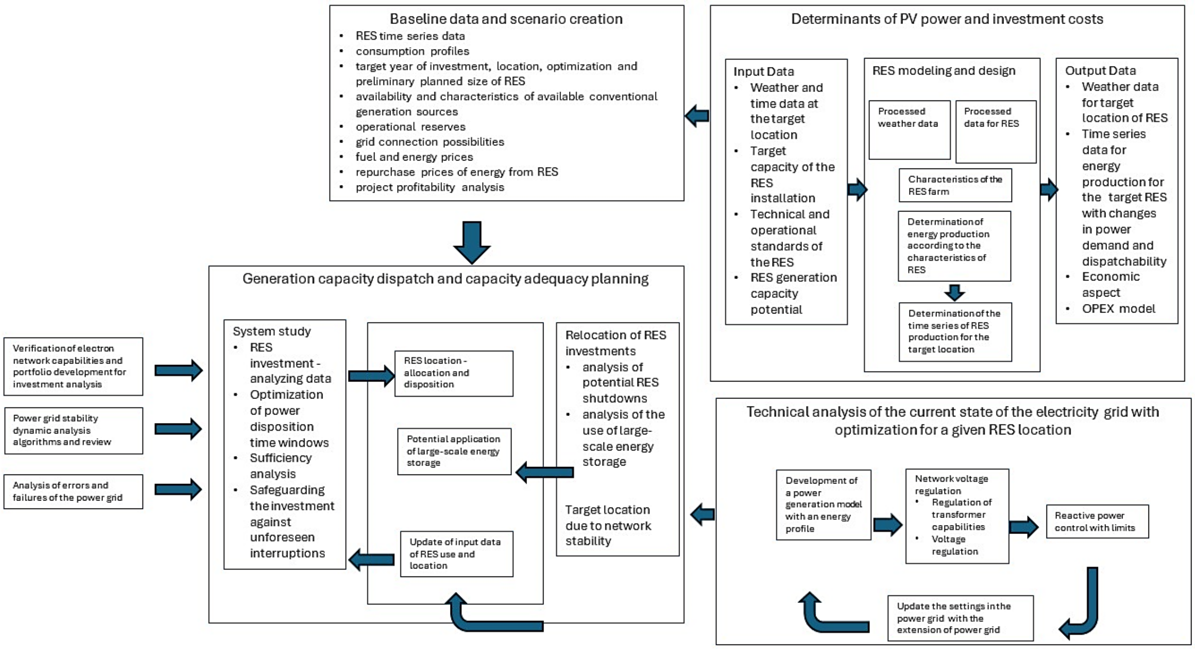

Figure 3. Typical planning aspects of connecting RES to the power grid, considering power quality, contingencies and investments.

Source: own elaboration based on (Khalid, 2024a).

Thus, it is essential to determine an effective model for RES sources and forecast their production. Wind and solar energy require much more intensive forecasting and scheduling due to their scope of application and intermittent and variable nature (Cheng et al., 2020). Therefore, short- and long-term renewable energy production and weather forecasts must be evaluated and studied (Sarshar et al., 2017; Hetzer et al., 2008; Naz et al., 2019). Unlike conventional generators, the unpredictability of RES sources limits their operation at total capacity, especially during peak hours. In addition, it satisfies additional load demands because it makes the system vulnerable to instability and power failures. As a result, grids that contain renewable energy sources need advanced energy management systems based on electricity availability, demand, energy unit prices, and storage and generation costs. In addition, the grid can consider renewable energy generation as a disruption from a power grid perspective if it represents less than 5-10% of total demand (Sgouridis et al., 2016). Likewise, the intermittent nature of renewable energy sources creates complications when planning the day-to-day operation of electric grids. Because renewables fluctuate over multiple time horizons, distribution grid operators must readjust system operations in real-time, for several hours or with day-ahead planning. Therefore, to meet load demand, the conventional generation system has to be constantly changed, as the RES output changes every minute. This cyclic operation hurts the system, putting pressure on the generators and reducing their efficiency. This problem becomes much more pronounced when combined with variable load demand. Rapid fluctuations in solar or wind power output affect the hourly load on the grid after the planning phase and even upset the balance between total demand and supply from second to second. Hence, the fundamental problem is to reduce the cost of regulating intermittent renewable energy sources (Alhammad et al., 2021).

In conclusion, photovoltaic systems can replace conventional synchronous generation on the power grid if placed, sized, and functioning correctly. However, their unpredictable output fluctuations must be considered, as they will affect energy flow and how the grid operates. In this regard, four basic parameters of power system operation can be distinguished, namely:

- power balance,
- power quality,
- optimal power flow,
- grid stability.

Power balance challenges include issues related to the short- and long-term balance of power system generation and demand. Grid capacity must be coordinated on a large scale to achieve system-wide balance. This task is difficult due to the unpredictability and uncertainty of RES sources. End users have the most stringent requirements, the most important of which is adequate power quality. Uninterrupted power supply, stable voltage and current conditions, and safe conditions in power outages are considered for power quality challenges. Challenges related to optimal power flow concern the efficient transmission and distribution of electricity. Frequency and voltage regulation in the power system and system restoration after power outages are significant challenges related to stability issues. The modularity of RES generators and the fact that these generators are not synchronous are the most critical factors contributing to stability issues. A detailed summary of RES integration challenges and problems with basic parameters is presented in Table 2.

Table 2.
Challenges of RES integration

Issue	**Challenge**	**Description**	**Impact**	**Relia-bility**	**Resi-lience**
Power balance	Limited availability of renewable energy sources of reproduction	According to the characteristics of most RES power generation technologies, grid frequency stability cannot be stabilized when RES generators are operating. This will lead to unforeseen power outages due to a mismatch between demand and generation.			x
	Inadequate forecasting of RES generators	Unplanned grid operation can be observed on the grid due to inaccuracies in forecasting RES output generation. The degree of losses can range from economic to technical and equipment damage.	x	x	
	Inadequacy in long-term generation operation	As the level of variable renewables on the power grid increases, the operational aspects of the grid in terms of seasonal and annual energy balancing will change, which will affect the timing of the synchronous generation system. As a result, the system may be susceptible to long-term system instability due to inaccuracies resulting from unpredictably variable RES output. Consequently, systematic generation deviations may prove economically challenging.		x	

Cont. table 2.

Power Quality	Voltage Flickering	Locally integrated RE through power electronics increases flicker, leading to shorter equipment life.			x
	Harmonics	The use of inverters in RES introduces additional harmonic distortion. This leads to shorter equipment life or equipment damage to end users.			x
	Low reliability during blackout	Renewable energy generators that continue to produce electricity in areas disconnected from the larger grid are susceptible to stability and power balance issues, leading to safety and operational concerns.	x	x	x
	Voltage overload at the distribution level	Connecting RES at low voltage on the grid leads to increased voltage impact. Excessive voltage at the peak of RES production or during periods of low power demand.	x	x	
Optimal Power Flow	Increased overall voltage profile	Connecting RES increases the overall voltage level, especially in impacted distribution areas.	x	x	x
	Limitation of network capacity	Existing grids may not be able to handle the power of renewable energy generators. If a RES shutdown is planned, it will result in power curtailment and losses for RES owners. An unplanned shutdown will leave the system vulnerable to failures and equipment damage.	x		x
	Increased potential instability and uncontrolled power at lower network levels	Uncontrolled connection of RES will result in increased unpredictability of power generation. This may result in increased curtailment of RES generators, stability requirements, and if unplanned, will lead to equipment damage.	x		x
	Low degree of controllability of RES	Connecting RES in the form of many unplanned capacities of small units will have an aggregate impact on power flow and system dynamics. This reduces the reliability of forecasting and planning, which can lead to systematic grid instability.	x	x	x
	Low level of RES monitoring	At low voltage levels of the grid, there is a lack of adequate metering equipment to complement the variability of renewable generation systems. As a result, there will be unobserved power flow, which can result in unscheduled grid operation that can be both technically and economically damaging.		x	x
	Limited network capacity	Connecting RES to the existing grid may require the construction of additional transmission lines. Otherwise, the grid will be exposed to RES capacity curtailment, reduced transmission capacity during planning phases, and capacity curtailment.	x	x	
Grid Stability	Limited ability to manage reactive power	Most renewable generation technologies have negligible reactive power input. According to grid standards and dynamics, transmission lines require reactive power support to maintain voltage standards. Therefore, the expansion of RES may be limited due to the resulting potential voltage violations. The lack of reactive power support will also affect power quality and stability, leading to curtailment or isolation of RES generators.	x	x	
	Reduced ability to detect faults	Fault detection and voltage instability may go undetected due to the relatively lower value of short-circuit currents in RES. This can cause complications in stable grid operation and isolation of RES microgrids.		x	x
	Reduce network inertia	An uncontrolled increase in grid frequency as a result of tripping an unstable RES source can lead to high grid instability. As a result, due to constraints related to the equality of demand and production, production curtailment or load reduction may be necessary to maintain the operational stability of the system.	x	x	

Source: own elaboration based on (Khalid, 2024b).

4. Challenges of reducing grid power in Poland and Germany

The EU's 2030 climate and energy targets will be helped by the *National Energy and Climate Plans* (NECPs) enacted by individual EU countries. In Germany, according to the current NECP, a 40.4% share of RES is planned to be achieved in 2030, a significant increase from the 30% in the previous NECP and almost double the 2023 projections. In the electricity sector, Germany plans to achieve an 80% share of renewables by 2030, a significant increase from the 65% share by 2030 from the previous NECP. In photovoltaic development, the German government plans to install 22 GW of photovoltaics annually, translating into 215 GW of cumulative installed capacity by 2030 and 400 GW by 2040. The plans thus represent a massive leap from the current capacity of 82 GW and the previous NECP target of 98 GW. The area of support in Germany is regulated by the *Renewable Energy Sources Act* (EEG Erneuerbare-Energien-Gesetz). It allocates €300 million in 2023 for direct subsidies for photovoltaic installations installed on rooftops with electric vehicles and energy storage.

In Germany, to balance production and consumption in real-time, it is envisaged that RES will develop smoothly according to need and, in conjunction with actual demand at a given location, integrate the energy market and combine sectors, e.g., by expanding energy storage capacity. Great emphasis is placed on increasing self-consumption, i.e., increasing the consumption of the energy produced from PV without injecting surplus into the grid.

The National Energy and Climate Plan does not set specific targets to support demand-side management at the distribution or central levels. In grid development, the National Plan recognises the importance of expanding power grids for properly developing renewable energy sources. According to the NECP, the rapid growth of renewable energy sources in Germany requires an adequate expansion of interconnections, which will be implemented simultaneously with the expansion of the national grid. Regarding transmission infrastructure, about 14,000 km of lines are planned in Germany, including 1400 km interconnections (SolarPower Europe, 2024). However, there needs to be details on which member states will be connected as a priority and with what capacity. Regarding the distribution network, Germany plans to expand it.

A preliminary version of the NECP update was prepared in Poland and submitted to the European Commission on March 1, 2024. The document submitted to the European Commission is a draft update of the 2019 *National Energy and Climate Plan 2021-2030.* The draft NECP sets a target of 29.8% share of RES in gross final energy consumption in 2030. Projections by Polish market experts estimate much more, and Poland could reach about 50.1% RES share in final energy consumption in the electricity sector in 2030 and 59.1% in 2040 (Ministerstwo Klimatu i Środowiska, 2024). In the 2030 outlook, onshore wind power (with an installed capacity of about 15.8 GW), photovoltaic installations (about 29.3 GW) and offshore wind power (about 5.9 GW), which will operate in the NPS from about 2026, will contribute most to the increase in electricity generation from RES. The document indicates the challenges that will arise as RES develops in Poland.

The increase in the share of RES in the national energy mix, mainly based on wind and solar, is variable over time. In Figure 5, you can see the energy mix of Germany (2023) and Poland (May 2024) for comparison. Noteworthy is the fact that Germany's RES is already more than 50%, and of this, the largest share is wind. In Poland, the share of RES is more than 33% of power, with the largest share being photovoltaics.

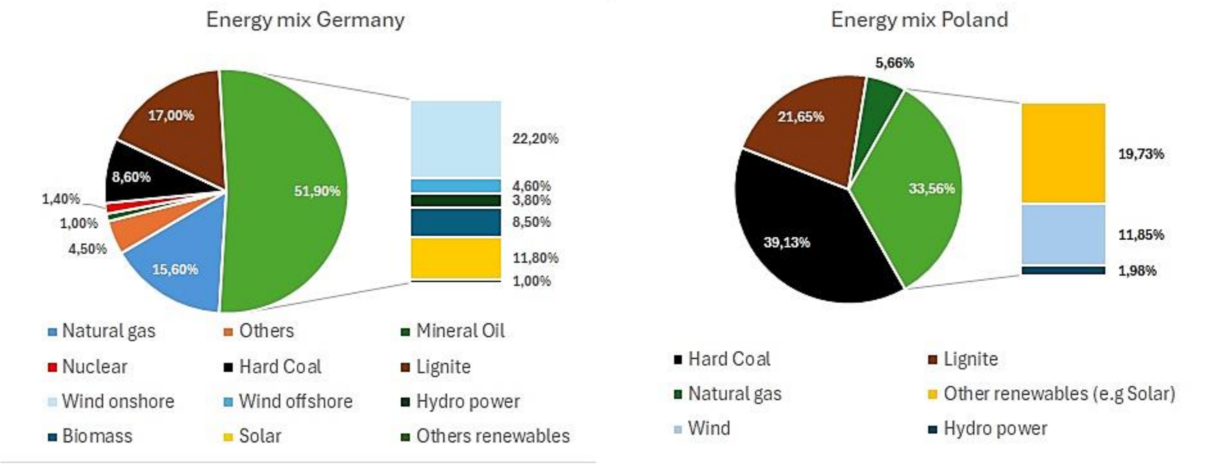

Figure 4. Energy Mix Germany (2023) and Poland (May 2024).

Source: own elaboration based on Clean Energy Wire and Rynekelektryczny.pl

This situation makes meeting the demand for electricity and power in the power system an increasing problem. One response to this challenge is to increase the flexibility of the power system. Currently, the flexibility of the power system is provided by conventional energy sources, particularly gas and coal-fired power generation units and pumped storage power plants. The ability to stabilise the grid depends on their technical parameters. The current rapid development of RES means that existing technologies need to be improved, and other flexible sources, including energy storage and appropriate Demand Side Response (DSR) management, should be used to stabilise the grid in the future. In the future, grid stabilisation will be achieved through greater cooperation between generators, consumers and operators, facilitated by the development of smart grids and smart metering. The National Plan envisages promoting greater participation of generators in future balancing and power markets. According to the NECP, the development of electricity system flexibility will be supported by the implementation of EU electricity market legislation, including the existing provisions of EU Regulation 2019/943 on redispatch (Article 13) or the formation of network tariffs (Article 18), and EU Directive 2019/944 on aggregation (Articles 13 and 17), active forms of market participation by the least active market participants (Articles 15 and 16) or flexibility services (Article 32). Accordingly, the goal of increasing the share of RES, energy storage, and DSR to ensure the flexibility of the electricity system has been defined. Adequate policies supporting the development of energy storage and the implementation of demand-side and supply-side mechanisms through the introduction of dynamic pricing and tariffs or DSR aggregation will help ensure this goal's realisation. According to the draft NECP, priority will be given to the further expansion and modernisation of electricity grids (transmission and distribution) to improve the capacity to receive energy from generation sources and to ensure adequate energy flow in the power system. In the future, this infrastructure is also expected to provide the ability to continuously exchange energy with the power systems of neighbouring countries and the European power systems more broadly. In this area, the Polish NECP envisages the dynamic development of cross-border connections by increasing the availability and capacity of current cross-border power interconnections. At present, the key to the country's energy security is the connection of the electricity systems of the Baltic States (Lithuania, Latvia and Estonia) to synchronous operation, which is planned for February 2025.

With the development of photovoltaic and wind installations comes the shutdown of PV installations by distribution grid operators on behalf of the national grid operator PSE, known as non-market reduction of generation of PV sources. Such a situation occurs if three phenomena occur: very nice weather with high sunshine, strong wind and low electricity demand.

In Poland, such a situation occurs most often on Sundays before noon on sunny and windy days. The critical factor preventing such a situation is proper demand forecasting by the national power system, which PSE does in Poland. An erroneous forecast can affect the improperly prepared power system, resulting in larger power reductions than expected. Another reason for reductions in grid capacity is the low flexibility of coal-fired power plants, which still make up a significant part of Poland's energy infrastructure. The installed capacity of coal-fired power plants is 32.7 GW, accounting for 58.5% of the total capacity in the country's energy mix, and is steadily declining. Shutting down coal-fired power plants for a short period is problematic and very costly. As a result, PSE is taking advantage of the flexibility of renewables-based sources, leaving conventional power plants at minimum capacity levels.

The first non-market reduction in PV generation occurred on April 23, 2023 (Wysokienapiecie.pl, 2023). The event was later dubbed "Black Sunday" and began a PV and wind turbine shutdown period. To balance the power system on that day, transmission grid operator PSE reduced the output of PV sources by about 2.2 GW. A communique published by PSE declared a "threat to the security of electricity supply" so that it could issue an order to disconnect some power plants from the grid. It announced an excess electricity production over demand in the Polish power system. The main reason was the high generation of photovoltaic sources due to the sunny day. Wind farms also supply a relatively large amount of energy. This procedure allowed PSE to issue orders to reduce power plants connected to distribution networks with a voltage lower than 110 kV. These are mainly medium and small wind and solar power plants and micro photovoltaic installations, which currently constitute one of the largest power sources in the power system. However, for technical reasons, it is not possible to manage PV micro-installations (installations of less than 50 kWp) due to the lack of direct communication with inverters. Currently, shutdown through inverter management is only possible for small and large installations built with a building permit under the obtained connection conditions. These installations, depending on the conditions notified by the DSO, have the appropriate telemechanics to enable remote management.

Considering the total installed PV capacity in Poland without micro-installations (capacity of 10.75 GW at the end of January 2024), the capacity of larger PV plants exposed to outages was 6.32 GW at the end of the first month of 2024. Before April 2023, PSE's actions to curtail RES generation included only wind farms. There were a few PV shutdowns in 2023, such as July 2 and October 8—later generation reductions involved only wind farms (December 25 and January 31, 2023). The first PV reduction in 2024 occurred on March 3. At that time, the non-market power reduction amounted to 815 MW from 12:00-13:00, 741 MW from 13:00-14:00 and 594 MW from 14:00- 15:00, covering larger PV power plants connected to the high and medium voltage grid. In addition to reducing the operation of photovoltaic systems, PSE also stabilised the Polish power system by, among other things, emergency power exports to neighbouring countries. Another reduction order took place on March 31, 2024, when PSE issued an order to shut down PV with a total installed capacity of 3.23 GW. The subsequent power reduction took place on April 15, 2024. On that date, a 2.5 GW reduction in PV capacity was ordered (against PSE's earlier forecast of 2 GW) and wind power curtailments. The curtailment peaked at 4.45 GW between 12:00 p.m. and 1:00 a.m. At that time, the total power demand was 17.4 GW. It is worth noting that the record for PV power generation in Poland occurred on April 9, 2024, at 10.65 GWh. The last recorded PV and wind power plant shutdowns occurred on May 1-5, 2024 (May long weekend). The most considerable PV capacity reduction was on May 1, 2024, at 12:00-13:00. It amounted to 4.749 GW against a planned 4.084 GW (Polskie Sieci Energetyczne, 2024), accounting for 75% of all PV capacity to be reduced in Poland. A parallel demand for wind capacity reduction of 0.862 GW was reported at the time. Table 3 shows the collected non-market reductions of PV generating units and wind turbines in the National Power System (NPS).

Table 3.
Non-market reductions of PV generation units and wind turbines in the NPS

LP	Date	Reduction PV [MW]	PV	Wind
1	23.04.2023	b.d.	Yes	bd
2	30.04.2023	2300	Yes	bd
3	02.07.2023	b.d.	Yes	bd
4	08.10.2023	b.d.	Yes	bd
5	25.12.2023	b.d.	No	Yes
6	31.12.2023	b.d.	No	Yes
7	03.03.2024	815	Yes	Yes
8	31.03.2024	3230	Yes	Yes
9	15.04.2024	2500	Yes	Yes
10	01.05.2024	4749	Yes	Yes
11	02.05.2024	3851	Yes	Yes
12	03.05.2024	1602	Yes	No
13	04.05.2024	4415	Yes	No

14	05.05.2024	3387	Yes	No
15	09.05.2024	957	Yes	No
16	12.05.2024	2392	Yes	No
17	13.05.2024	1772	Yes	No
18	15.05.2024	3484	Yes	No
19	16.05.2024	4150	Yes	Yes
20	17.05.2024	3086	Yes	No
21	19.05.2024	2114	Yes	No
22	26.05.2024	2843	Yes	No

Source: PSE (https://www.pse.pl/komunikaty-osp).

The reduction order notified by PSE entails the payment of appropriate compensation to owners of the affected generating units. The above situation is defined by Article 13 (7) of EU Regulation 2019/943, which specifies that the so-called non-market redispatch is subject to financial compensation paid to generators. Unfortunately, the current regulations do not define specific rates for reducing electricity generation. Generators are supposed to receive compensation covering lost revenues due to the reduction in electricity generation. Despite the relevant regulations, owners of photovoltaic installations subject to curtailment have received refusals from DSOs (Money.pl, 2024). Contracts containing a possible exclusion from compensation will be enforced by the DSOs as part of the connection agreement. In such a situation, DSOs will first limit capacity on a market basis, i.e., installations containing provisions allowing DSOs not to pay compensation. In the second place, excluders will be entitled to production limitations with a guarantee of compensation on a non-market basis.

Due to the significant capacity volumes of wind and solar RES sources and the shutdown of nuclear power plants, the situation in Germany is much more complicated. The German power system increasingly relies on variable renewable energy sources, challenging the country's grid operators for many years. In Germany, special measures known as "re-dispatch" are used to achieve grid stability, which ensures a balance between supply and demand. A significant challenge in Germany is the specific distribution of RES, with wind power in the northern part of Germany and PV in the southern part, where there is more electricity demand due to the industry's location. Thus, from Germany's perspective, an adequate energy connection between the northern and southern parts of Germany is crucial. For grid stability, the electricity injected into the grid must equal the amount withdrawn from the grid at any given time. This is usually achieved through the energy market, where power plant operators produce enough electricity to meet demand, i.e., by supplying what has already been sold on the exchange. Grid operators receive a list of power plant "dispatches" based on market data one day in advance, which allows them to see if adjustments are needed to keep the grid running smoothly (Kerstine Appunn, 2016). Operators in Germany can use three different types of redispatch measures:

- ordering conventional power plants in northern Germany to reduce production to "make room" on the grid for a large influx of wind power,
- temporarily shutting down wind turbines (only as a last resort since renewables have priority on the grid),

- ordering conventional power plants in southern Germany to produce more electricity to meet demand from consumers in the south, whose suppliers have bought northern German wind power that cannot be supplied.

All of these actions result in additional costs for consumers. When grid operators order power plants to curtail production, they must compensate them for the price of the unsold electricity for which they would have been paid (minus the expenses that power plants save on fuel). When grid operators order renewable energy producers to disconnect from the grid, power producers must also be compensated for some of the lost profits.

In 2014, re-dispatch interventions were required for 330 days (232 days in 2013), affecting 5197 GWh and costing 186.7 million euros (132.6 million in 2013). The redispatch costs are passed on to consumers as part of the grid charge that households pay in their electricity bills. Re-dispatch costs in Germany continue to rise. For example, about 10.5 TWh of electricity was lost due to curtailment in 2023, compared to 8 TWh in 2022, and nearly doubled in two years. However, the cost of deliberately reducing production by some installations while implementing additional capacity in other regions was lower in 2023 than in 2022, falling from €4.2 billion in 2022 to €3.1 billion in 2023. The cost and level of congestion in Germany between 2019 and 2023 can be seen in Figure 5.

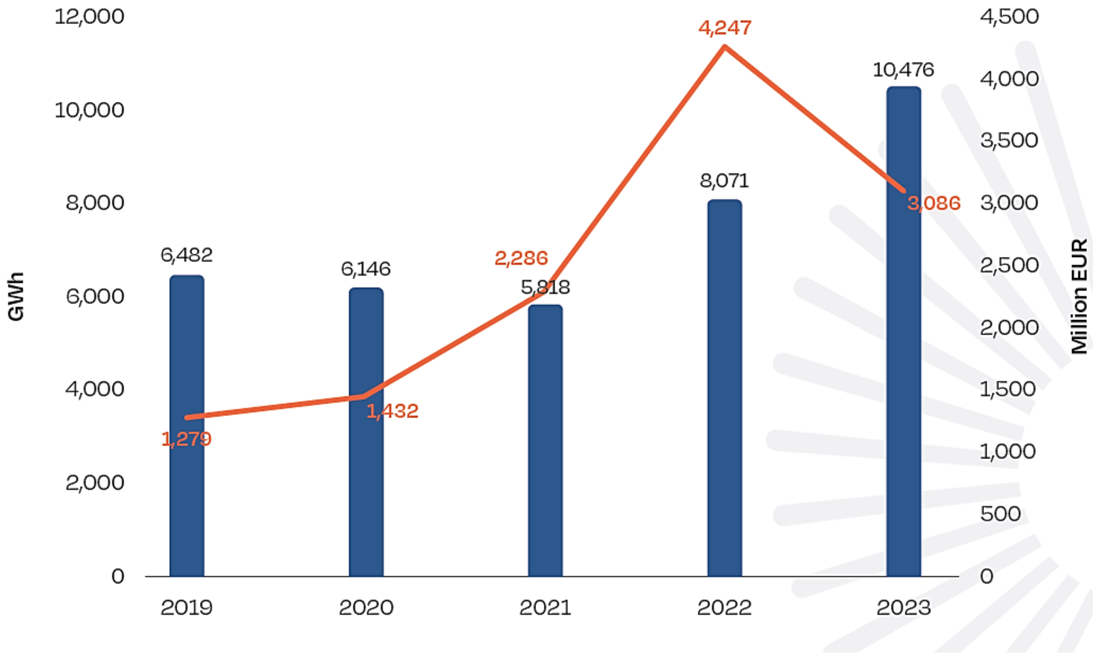

Figure 5. Cost and level of grid congestion in Germany 2019-2023.

Source: (SolarPower Europe, 2024).

The reduction of 10.5 TWh of electricity production by RES in 2023 corresponded to about 2.3% of Germany's total annual electricity production. At the same time that the operation of RES installations in some regions was reduced due to grid bottlenecks, fossil-fuel power plants in the other areas (in western and southern Germany) had to come online to cover the reduced production. Building wind turbines relatively far from energy consumption centres has contributed to the high demand for redirection measures, as long-distance transmission lines are among the most congested parts of the power grid. The lower cost of maintaining grid stability in 2023, despite the increased demand for re-dispatch, is mainly due to the drop in energy prices after 2022 (Wehrmann, 2024).

5. Possible directions for regulatory and administrative action

Due to the dynamic development of RES, grid capacity will continue to be reduced. Experience from the German market shows that the cost of maintaining the power system will increase with the development of RES

5.1. Development scenarios for the German market

One idea to solve the re-dispatch problem in Germany is to introduce new regulations. The German government is considering steps to allow more green electricity, the production of which is currently limited due to transmission bottlenecks in the national grid. Under the proposed reform of the country's Energy Industry Act (EnWG - Gesetz über die Elektrizitäts - und Gasversorgung. Energiewirtschaftsgesetz), the German government intends to improve conditions so that electrolysers or flexible consumers can use renewable electricity locally at lower prices during periods when it would otherwise be restricted due to a lack of grid capacity. The instrument would take effect on October 1, 2024, and oblige transmission system operators to auction renewable electricity that is currently unused due to grid congestion. This should make it much cheaper (Kyllmann, 2023). Germany's experience shows that it is necessary to continuously expand the grid and introduce incentives and programs to support the development of energy storage.

SolarPower Europe experts point out that a critical technology to keep curtailment levels low in Germany will also be easily deployable energy storage (SolarPower Europe, 2024). The rapid installation of energy storage facilities will avoid growing curtailments and enable renewables' rapid growth. Still, it will also help reduce expenses related to managing grid curtailments, which have risen significantly to €3.1 billion in 2023, 2.5 times more than four years earlier. Currently, during times of excess capacity, renewable energy producers are compensated for withholding electricity, while fossil fuel plants are rewarded for increasing production during periods of low renewable output. As renewable capacity increases and conventional sources are phased out, the number of hours with supply-demand imbalances will increase, leading to higher capacity curtailment costs and grid management costs unless energy storage facilities are successfully deployed. Currently, the German market is the largest market for energy storage, with an installed capacity of 5.9 GWh at the end of 2023, compared to 2.3 GWh of energy storage capacity in 2022. SolarPower experts forecast further dynamic development of energy storage in Germany, maintaining first place by 2028 with a 20% share of the total European market of 78.1 GWh.

Another challenge facing the German market is the stabilisation of the power grid as a result of RES development. One solution to this problem is the use of so-called grid-forming services. These services are an extension of energy storage and inverters with additional functionality. Today, energy storage systems can replace conventional power plants thanks to new stability system services. Grid support systems for large energy storage solutions are being placed at strategic points in the transmission network. They increase the flexibility of existing transmission systems, reduce bottlenecks, and simultaneously reduce the need to implement costly redistribution measures.

The first country in Europe to widely deploy these technologies is the United Kingdom. In Germany, the first smaller-scale projects were carried out in 2019 in the Bordesholm region (SMA Solar AG, 2020). As part of a research project at the end of 2019, Bordesholm Public Works, in cooperation with TH Köln and SMA, simulated power failures over a large area. To do this, the Bordesholm plants were isolated by a synchronous power switch from the European power grid for one hour. About 8000 Bordesholm residents and all households, plants, and institutions were continuously supplied with electricity using renewable energy. The final technical verifications were completed in 2022 (German Energy Solutions Initiative, 2022).In Germany, the market for non-frequency-based ancillary services is expected to be launched in 2024, making Germany the first continental European market for grid stabilisation services (Intersolar, 2024).

5.2. Development scenario for Poland

Against the backdrop of the current situation in Germany, Poland is only at the beginning of the search for solutions. As a first step, the right direction is to strengthen the role of renewable energy sources for stabilising grid parameters. Currently, this role is assigned to conventional power generation, which in the case of Poland involves using coal-fired power plants for this purpose. However, these power plants are characterised by low flexibility of operation with high failure rates. In addition, they are unsuitable for rapid power changes because of the real risk of damage.

On the other hand, it is estimated that Poland needs about 7-8 GW of power to stabilise the grid. Therefore, PSE must consider their requirements for the minimum power that conventional power plants provide. Thus, with low customer demand, only 6-7 GW of space remains for other sources to operate unless energy is exported to neighbouring countries or stored (e.g., in pumped storage plants). As a result, conventional power plants provide adequate inertia to determine the parameters of the grid, ensuring its stability.

However, as the share of RES in the Polish energy mix increases, the inertia of the power system decreases. The decrease in inertia leads to the rise in the amplitude and dynamics of frequency fluctuations following disturbances in power supply resulting from the variable nature of renewable sources. Currently, however, power market participants are discovering the ability of RES to provide non-frequency system services, which, together with flexibility services, are complementary services that stabilise the power grid. These services are already standard in Western European countries under the name above of grid-forming.

Photovoltaic inverters commonly used in PV installations are current sources and do not change grid parameters; they only adapt to them. Grid forming and the functionality of the new inverters, which become a voltage source in this arrangement, will allow renewable energy, which is far more flexible than conventional power, to change grid parameters. This will free up capacity backed by conventional power generation, providing more significant opportunities to manage unstable energy sources. In Poland, these services are currently being designed and analysed by the Polish Power Grid. Thus, the development of grid forming and other services like DSR will contribute to increased grid flexibility. However, this requires significant investment in the expansion of energy infrastructure, and in particular in the development of large-scale energy storage facilities.

Flexibility services, of which DSR is one, allow the level distribution system operators to introduce solutions to ensure the involvement of consumers, storage and generators in managing network congestion. Complementary to flexibility and system services are power market services and balancing market services. However, since energy prices in the balancing market at times of oversupply remain high from the perspective of the European market, i.e., about PLN 300 MWh, from the perspective of Polish conventional power plants, it is below their production costs. This results in a situation in which conventional power plants exacerbate losses, and on the other hand, Poland cannot export surpluses outside the country.

One of the main directions for RES development is the spread of energy storage. This is a good solution in every market segment, i.e., for individual customers, businesses, and large-scale storage. The development of energy storage can be stimulated by subsidy programs like My Current or supported by the National Recovery Plan (NRP). However, it should be linked to arbitrage and dynamic tariffs.

The combination of opportunities brought by energy storage and smart energy management functions, such as recharging electric cars, heating domestic water in buffer tanks, or automatically running air conditioning from surplus PV energy, will become increasingly popular.

Equally, technologies available in modern inverters, like ZeroExport, a power guard that prevents PV energy from entering the grid, or reactive power management in the form of the Q(U) function, are now helping to stabilise the power system.

6. Conclusion

In the period under review, Europe, including Poland, is experiencing a very intensive development of RES, particularly photovoltaics, which requires an extensive and adapted transmission infrastructure. At the same time, the dependence of solar power plants on atmospheric conditions and the increasing frequency of extreme weather events pose more and more challenges to the transmission grid operator. Due to the significant challenges posed by the rapid development of distributed power, it is essential to continuously modernize the power grid toward smart grids by conducting support programs to develop the national grid infrastructure. It is essential to increase the flexibility of the power system, which is becoming a critical factor in maintaining the stability of its operation and reducing the loss of energy not generated from RES due to the necessary shutdown.

Non-market reduction in the generation of photovoltaic sources will become increasingly common in Poland, Germany, and other European countries.

Equally, the share of energy storage in the power system is growing slower than it is based on actual demand, and the cost of implementation is still high. This results in a situation where photovoltaic power generation reductions remain the cheapest and most effective form of power system management. Suppose the number of reduced hours per year is a critical mass. In that case, it will not be a significant stimulant for developing energy storage, flexibility services, and system services. Therefore, even in a mature power system with much greater energy storage capacity, such measures will continue to be an instrument readily used by power market regulators.

Author Contributions

Conceptualisation, A.M-F., K.N and A.B.; methodology, A.M-F. and K.N.; data curation, A.M-F., K.N and A.B.; writing-original draft, A.M-F., K.N and A.B. All authors have read and agreed to the published version of the manuscript.

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Data are contained within the article.

Conflicts of Interest

The authors declare no conflict of interest.

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