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Safe Path for the Transformation of the Polish Energy System Leading to Its Decarbonization and Reliable Operation

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Abstract: The European Union's energy policy, which aims to achieve climate neutrality by 2050, requires substantial changes in the structure of the energy sources used for power generation. The paper considers the possibilities of increasing the pace of the Polish energy system transformation by replacing coal sources with renewable energy sources using energy storage. It is demonstrated that in the analyzed period until 2040 it will be possible to ensure the required level of the system's energy supply reliability by supporting the system with energy storage. The assessment of the system reliability was carried out based on the LOLE and LOLP indicators, selecting the system structure in such a way that for the hourly energy demand characteristic adopted in the analyzed year, the LOLE was less than 3 h. The required capacity and power of the storage systems depend on the level of the demand for energy and power. The results of the analyses indicate that for the linear trend in the growth in the demand for energy, nuclear power plants with the total power of 8.8 GW have to be installed in the energy system. However, with a significant rise in the power demand and the decommissioning of coal units, balancing the system using other sources with a dominant share of renewable sources will be insufficient. It will therefore be necessary to use the energy storage with a capacity above 11 GWh and a total power above 2 GW.

Keywords: energy system; energy transition; reliability; energy storage

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1. Introduction

The climate agreement reached at the Paris Climate Conference (UNFCCC COP21) in December 2015 was ratified by more than 180 countries [1]. The primary aim of this agreement was to keep the temperature rise below the level of 2K compared to the preindustrial age.

In 2019, the European Commission presented the European Green Deal—a set of policy initiatives aimed at ensuring that the EU will have become climate neutral by 2050 [2].

In line with the aim to achieve neutrality in carbon dioxide emissions by 2050, the European Commission's long-term strategy describes a number of paths to achieve decarbonization levels of 80% to 100%. They all have serious implications for the energy sector, particularly the electricity sector.

A common feature of all the paths is that they require a more flexible energy system to integrate unstable RES technologies, e.g., solar photovoltaics and wind farms, with the other energy sources to ensure system reliability. The large-scale integration of wind, solar, and battery storage is a key feature of new energy systems based on renewable energy sources. However, integrating these sources raises many challenges [3]. In the paper in [4], the interaction mechanism of a hybrid energy system consisting of solar and wind sources and energy storage was investigated. In the paper in [5], the use of a battery energy storage system (BESS) as a transmission system resource that provides increased transmission capacity is discussed.

This goal can be achieved by the utilization of different energy storage technologies.

Energy storage will ensure flexibility across all time scales. The typical battery discharge time is measured in hours. In the case of pumped-storage batteries and seasonal water storage facilities, the discharge times range from a few hours to several months, and system integration has discharge times ensuring adequate flexibility to meet the needs related to seasonal variability [6].

Therefore, the proper implementation of energy storage technologies is of paramount importance for a successful transition to an energy system largely based on unstable RES technologies. This issue is investigated in many scientific publications. In [7], the authors present observations related to the design and creation of national low-emission strategies in countries such as Australia, Canada, Brazil, China, Russia, Japan, and the Republic of Korea.

The work in [8] proposed to give insights into the EU citizens' pre-pandemic perception of some key renewable energy transition, sustainability, and resilience factors, which may be crucial, with a view to finding prime energy policy indications that are useful for the post-pandemic recovery.

In [9], an analysis of the quantitative impact of the capacity of energy storage systems on the power grid reliability was conducted, along with ways to mitigate energy supply limitations.

The authors of [10] analyze energy system scenarios that make it possible to achieve an 80% reduction in carbon dioxide emissions in Japan by 2050.

The paper in [11] uses a detailed capacity expansion and hourly operation model to investigate the possibility and the cost of reaching different levels of planning reserve margins (PRM) in the multi-regional context of the North American northeast.

The authors of [12] present models of transition paths to a low-emission regional power system using hydrogen energy. In [13], the authors assess emission trajectories and the transformation of the energy systems of 11 major economies of the world. Energy system modeling was used in [14] to explore the paths leading to climate neutrality in the EU by 2050 and 2070 and to analyze their consequences. The impact of variable renewable energy resources on power system reliability in the United States was discussed in [15].

An approach to the assessment of the power system reliability, taking into account the uncertainty of wind energy, is discussed in [16]. The paper in [17] provides policy recommendations to plan for a shift to dual or winter-peaking power systems in the United States.

The assessment of the reliability of a complex power system in the presence of renewable generation is discussed in [18]. The authors of [19] use a power system model optimizing cost-effectiveness to investigate the technical and economic rationale for investing in new nuclear facilities in the UK's net-zero-emissions power system. The aim of the authors of [20] was to make a critical and systematic review of the impact of the reliability of energy storage systems on the reliability of power systems.

The paper in [21] examines the external benefit related to charge and discharge operations of hydroelectric storage power plants, as applied to the case of the northern area of the Italian wholesale electricity market.

The authors of [22] put forward a model for long-term planning of power generation, containing detailed technical and economic characteristics of hydrogen and heat storage.

The impact of hybrid renewable energy systems on the reliability of the system of energy distribution is discussed in [23].

A case study is performed in [24] considering research into the expansion of the Brazilian energy system, where the share of renewable sources exceeds 80% of the installed power on the horizon by 2029.

In [25], the participation of the energy storage system in the management of the demand for energy is investigated.

The authors of [26] present a simulation framework for medium- and long-term operation of a large-scale hybrid system of energy generation enhanced by a cascade hydroelectric energy storage system.

In [27], the methods of linear programming optimization were used to explore scenarios that could mitigate climate change by increasing the use of solar and wind energy, reducing coal consumption, and integrating energy storage to enhance the power system flexibility.

Sustainable transition pathways with a high share of variable renewable energy in coal-based energy generation systems are discussed in [28].

In [29], a method of optimizing the capacity of an industrial-scale hybrid wind–photovoltaic–electrolysis–battery system was proposed.

The changes in the structure of the Polish power system and the consequences thereof are discussed in [30]. The authors of [31] provide a review of the existing research on ESS reliability assessment, encompassing various methods, models, and reliability indicators, and they offer an analysis of future research trends in ESS reliability. The paper in [32] offers an overview on potential energy storage solutions for addressing grid challenges following a "system-component-system" approach. The energy storage technologies and their power electronics integration in the grid are described at the component level, considering the latest scientific trends, including the hybrid energy storage concept. The aim of the work in [33] is to provide a detailed overview of BESS-related aspects, focusing on the applications, developments, and research trends of hybrid installations in the end-user sector. A novel methodology for analyzing hybrid wind turbine–photovoltaic off-grid systems with battery storage is presented in the work [34].

The strategy for the transformation of the German energy system was discussed, among other subjects, in the DNV Energy Transition Outlook Germany 2025 [35]. According to the system development plans presented in this study, in 2040 the German energy system should have 53 GW of gas or hydrogen sources, 10 GW of hydropower, 264 GW of PV sources, and 63 GW of PV sources with storage, as well as 142 GW of onshore wind and 57 GW of offshore wind. Before 2040, the last coal sources will be withdrawn, and the use of nuclear energy is not planned. The authors of the study believe that a system with such a structure will provide the necessary electricity supplies.

The above review of the literature was mostly concerned with transformations of energy systems and cited articles discussing, among other subjects, planned changes in the energy systems of Australia, Brazil, Canada, China, India, Indonesia, Japan, Korea, Russia, the United States, Great Britain and the European Union. In each of these systems, the fundamental role is played by renewable energy sources supplemented by energy storage. In many cases, an important role is played by the nuclear power plants, hydroelectric power plants, and gas units present in these systems. In comparison to these systems, the situation of the Polish energy system is different; this is primarily due to the dominant share of coal units, which, according to the policy of the European Union, should be closed. The specificity of the Polish system is also the lack of nuclear power plants in its structure, which also significantly hinders the process of its decarbonization. In such an initial state, changes in the structure of the Polish energy system must first and foremost take into account the requirement of energy security, and the process of replacing coal sources with other energy sources, e.g., renewable sources, must at all times ensure full replacement of the power of the source being liquidated. This article examines this issue by analyzing the possibilities of using appropriate energy storage systems for this purpose. In the absence of the possibility of balancing the system, other necessary stable sources of power are considered, e.g., nuclear units.

Due to the specific nature of the transformation of the Polish energy system discussed above, resulting from its current structure, the rapid growth in the number of new renewable sources and the pressure to quickly shut down coal units pose a serious risk of a loss of system reliability. The aim of this article is to indicate safe paths for the transformation of the system, showing possible changes in the structure of the system that will allow the required level of reliability to be maintained. The necessary power and capacities of energy storage systems were determined, which would allow the management of surplus energy from renewable sources. Analyses were carried out for several variants of the increase in demand for power until 2040.

The article is divided into seven sections. Section 2 presents the role of energy storage in the energy transformation processes, as well as the existing and planned investments in large energy storage systems in Poland; Section 3 shows the evolution of the installed capacity structure in the system in the last ten years in Poland and compares it with the structure of energy sources in the entire European Union; Section 4 describes the adopted methodology for analyzing system reliability; Section 5 shows various planned structures of the Polish energy system in 2035 and 2040; Section 6 presents the results of optimizing energy storage parameters that could supplement the Polish energy system by providing it with the required level of reliability. A summary of the analyses performed is included in Section 7.

2. The Role of Energy Storage in the Power System Transformation Process

The ambitious targets related to the need for energy transition set out in the European Green Deal, as well as the Fit for 55 package, represent a major challenge for the power sector, which is still largely based on conventional power generation. Reducing emissions and finally achieving climate neutrality in 2050 require much faster development of RES-based power engineering than before. In addition to the technical and infrastructural challenges arising therefrom, one of the main problems that needs to be addressed is the unstable profile of energy production from renewable energy sources.

The development of power generation based on RESs will be possible if conventional power systems ensure adequate control and are able to compensate for the unstable operation of renewable sources; this instability is primarily due to Poland’s climatic conditions, which impede their efficient use. The problem could be solved by accumulating generated “excess” energy in energy storage facilities. In addition to electricity storage, it is also justified to develop heat storage and systems accumulating heat produced, e.g., in CHP plants, especially in the summer months, when the power achieved by cogeneration units exceeds the heat demand significantly. The construction of heat accumulation systems also enables optimization of the cogeneration system operation by operating the gas-steam unit with maximum thermal and electric power when electricity prices are high, shortening the working time of units and thus reducing service costs or minimizing the operation of peak-demand boilers during the transition period, which will significantly contribute to a faster rate of the transformation.

Energy storage guarantees greater flexibility and balance in the power grid, providing support for intermittent (unstable in relation to demand) renewable sources. In addition, their advantages also include the following [20]:

- Shifts of consumption over time—thanks to energy storage, prosumers and all users can use stored energy when it is needed;
- Improvement in power supply reliability, especially in places where the distribution infrastructure is poorly developed;
- Stabilization of grid parameters—using energy storage, distribution system operators can smooth the grid load curve when considering power generation;
- The possibility of connecting more RESs without having to invest in the transmission infrastructure.

Energy storage can be divided according to the size and the applied technologies, which include the storage of mechanical, electrochemical, electrical, chemical, and thermal energy [36,37]. According to that, the following are distinguished: pumped-storage power plants, electrochemical batteries, supercapacitors, fuel cells, superconducting energy accumulators, kinetic and pneumatic energy accumulators, liquefied air tanks, storage tanks using heat pumps, and hydrogen storage facilities [38].

The most common form of large storage facilities are pumped-storage power plants, which have been in use for several decades and account for 95% of the world's resources, with a total power of 184 GW. They convert electricity into the potential gravitational energy of water. Their use consists in pumping water from the lower reservoir to the upper one at a time when electricity production exceeds the demand, and then at peak hours. When the electricity consumption is high, the reverse process takes place. Pumped-storage power plants are powerful energy storage facilities with very high capacity and high energy efficiency.

In fact, pumped-storage power plants are the largest energy storage facilities in Poland, providing a total power of about 1.75 GW and consisting of two large plants: Żarnowiec (716 MW) and Porąbka-Żar (500 MW); there are several smaller ones located in Solina, Żydów, Niedzica, and Dychów. These power plants are specific energy accumulators and are necessary to compensate for the instability of power plants based on wind or solar energy. They are prepared for a quick start-up and adjusted by power to meet the regulatory and intervention needs of the National Power System. In the past, their main task was to smooth out daily fluctuations in electricity consumption, but now, their main function is to provide regulatory services.

In addition to the above-mentioned operating power plants, in Lower Silesia it is planned to resume the construction of the 750 MW pumped-storage power plant "Młoty". The construction will have been completed by 2030.

Energy can also be stored using technologies based on electrochemical batteries or the so-called battery energy storage systems (BESSs), where stored chemical energy can be converted into electrical energy if necessary. As it is most often modular in nature, this solution is not subject to any land limitations, unlike other energy storage methods. Currently, lithium-ion (Li-Ion) technologies prevail among the installed battery storage systems.

Other types of batteries using chemical processes include lead–acid, sodium-ion, sodium–sulfur, and flow or liquid batteries.

In Poland, investments in the form of battery (chemical) energy storage (BES) facilities are also being made, e.g., the project in Bystra near Gdańsk (with a power output of 6 MW and a capacity of 27.3 MWh) or in Cieszanowice in the Łódź region (with a power of 3 MW and a capacity of 774 kWh). More investments of this type are being planned, e.g., in the vicinity of the Żarnowiec pumped-storage power plant. This battery energy storage system, with a power output of at least 205 MW and a capacity of at least 820 MWh, will create a hybrid system in combination with a pumped-storage power plant. The total power and capacity will reach more than 920 MW and more than 4.6 GWh, respectively.

3. Evolution of the Structure of the Polish Energy System Against the Background of Changes in EU Systems

The energy mix in individual European Union member states is fundamentally different. It depends, among other factors, on the geographical location of a given country, the availability of energy resources, such as coal, oil, and natural gas, water conditions, and the country's wealth. Below, Figures 1 and 2 show changes in the structure of energy sources over the last 10 years in Poland and in the European Union as a whole [39].

Since the post-war times, with its significant resources of both hard coal and lignite, Poland has based the development of its power sector on these raw materials. The initiatives undertaken to build nuclear power plants have not been implemented. For several years now, the coal sources have been supplemented with gas power plants and, in the last decade, with wind power plants. As shown in Figure 1, since 2020 the Polish energy system has experienced a huge increment in the power obtained from renewable sources, mainly wind and solar power plants. At the same time, the number of coal-fired units has been decreasing, which means that in the next two years the total power of renewable sources will exceed the power of sources based on the combustion of hydrocarbons. But this situation of RES power being higher than the power of conventional sources already took place in the EU countries in 2017. It should also be noted that a significant role in the EU energy mix is played by nuclear power plants.

The installed power of wind and solar power plants is increasing, but the share of electricity produced from these sources in the entire volume of produced energy is much smaller compared to what is suggested by the installed power proportions. This is due, among other things, to the poor wind and insolation conditions in Poland. A comparison of the growth rate of electricity production from renewable sources in the last 10 years is shown for Poland in Figure 3 and for the European Union in Figure 4.

The share of energy produced from renewable sources in the last period exceeded 25% in Poland and 45% in the EU countries. It should be noted, however, that the rate of the growth in "green" energy production in Poland is much higher than in the European Union treated as a whole. One of the possibilities for the faster replacement of energy produced from coal sources with renewable energy is the wider use of renewable energy storage.

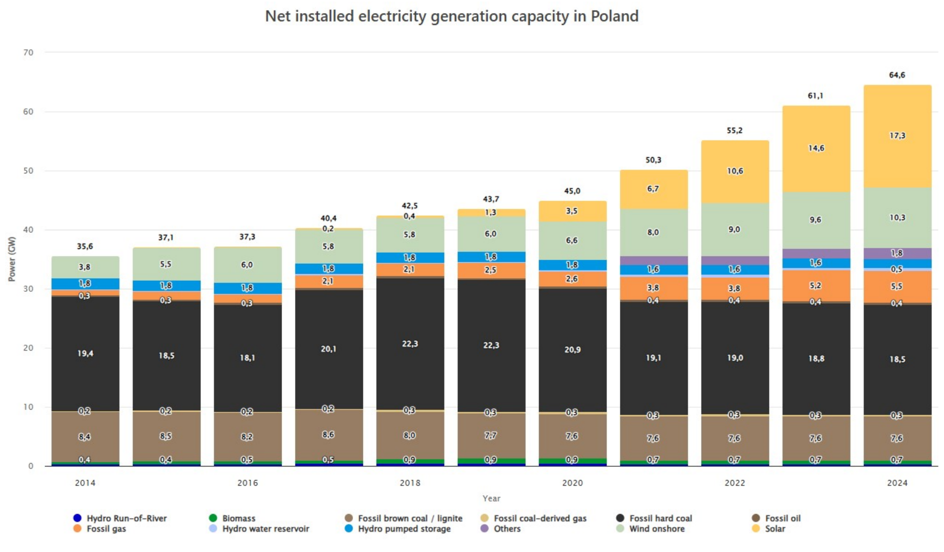

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Figure 1. Evolution of the structure of energy sources in the Polish energy system [39].

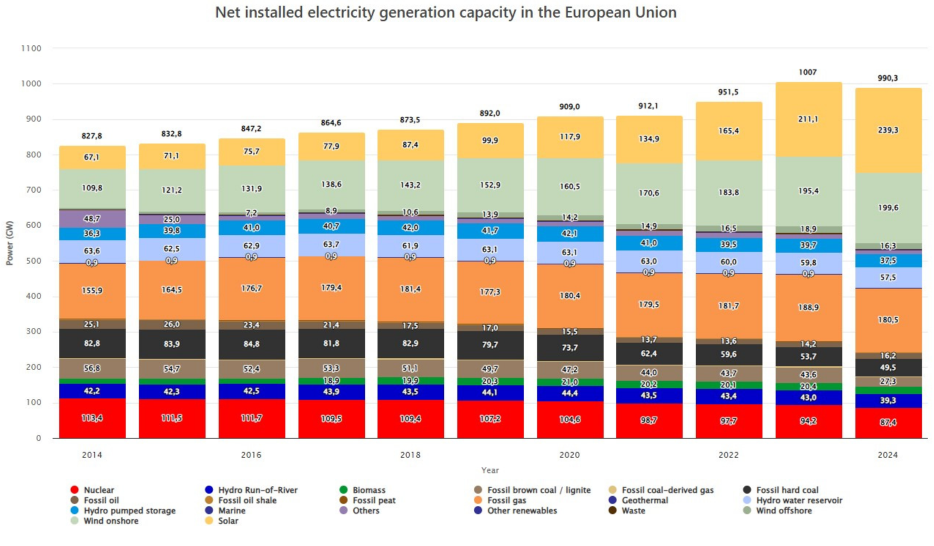

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Figure 2. Evolution of the structure of energy sources in the European Union [39].

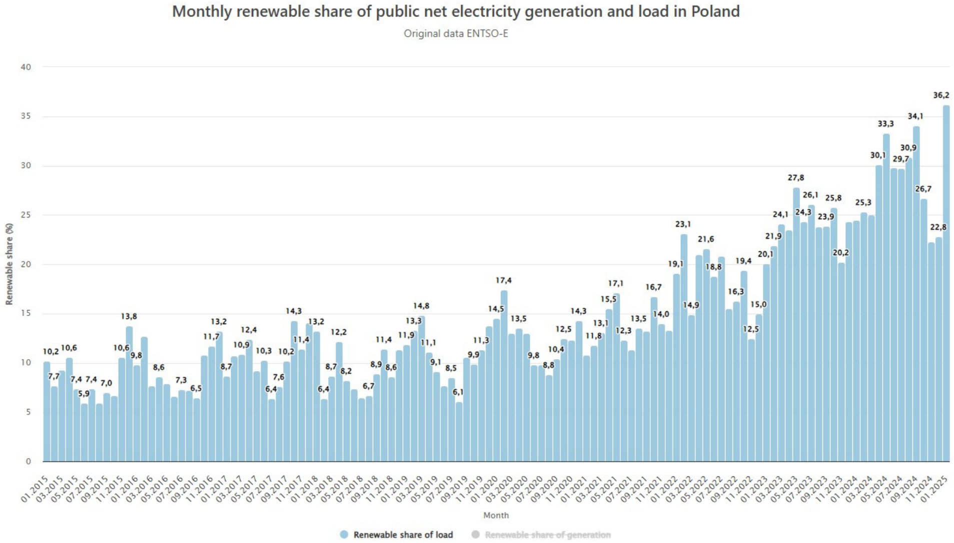

Figure 3. Share of electricity produced from RESs in Poland in 2015–2024 [39].

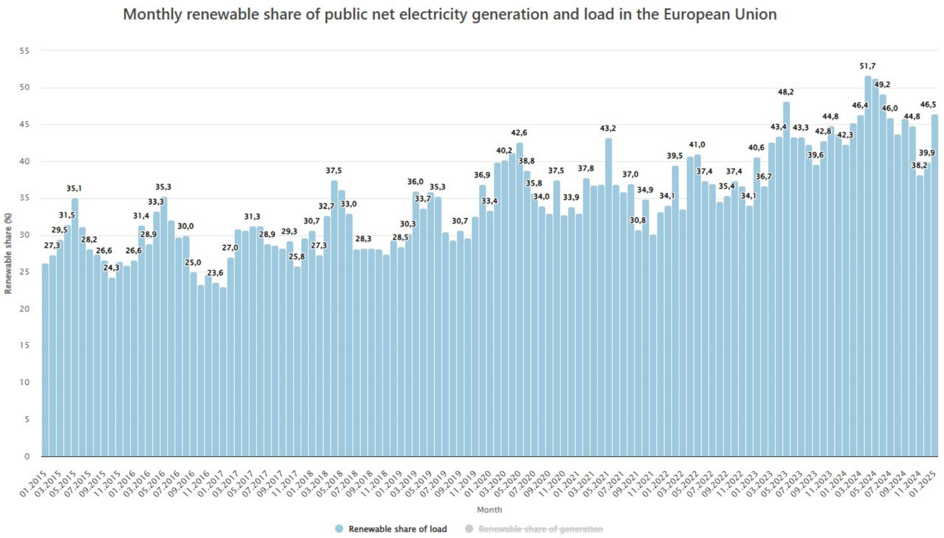

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Figure 4. Share of electricity produced from RESs in the European Union in 2015–2024 [39].

4. Selection of the Energy System Structure with Storage Ensuring the Required Level of Reliability

The previous section presented a comparison of the structures of the Polish and EU energy system. In order to compare the reliability of the current system and the planned system with energy storage, calculations were made of the cumulative distribution function of power F(P) for each of the systems under consideration [40–43]. LOLP and LOLE are the most widely used indices in generation adequacy evaluation. The LOLP index, which expresses the probability of the system not being able to satisfy the demand for power, is defined as follows:

$$LOLP\left(P_{Dp}\right) = P\left\{P_G < P_{Dp}\right\} \tag{1}$$

where P—probability of a situation in which the system's total generating capacity is smaller than the demand, P_G—the system's available power, and P_{Dp}—peak power demand.

Figure 5 shows schematic diagrams of the cumulative distribution function of power for two systems with different structures designated as system 1 and system 2. For a given power demand P_{Dp}, the LOLP values can be calculated based on these diagrams, respectively, for system 1 as the $LOLP(P_{Dp})_1$ value and as the $LOLP(P_{Dp})_2$ value for system 2.

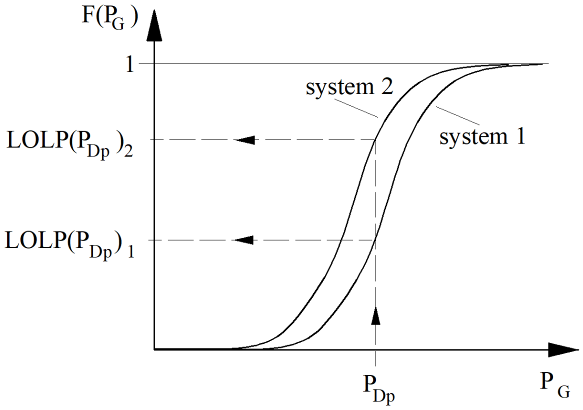

Figure 5. LOLP value calculation method.

The second indicator used in further analyses is the LOLE (loss of load expectation), which determines the total number of hours in a given period (most often a year) when the system is unable to generate enough electricity to meet the demand. The LOLE is therefore the expected value of the sum of the duration of power deficits in the analyzed period, and it is calculated as follows:

$$LOLE = \sum_{k=1}^{a} \Delta t_k LOLP\left(P_{Dp}\right) \tag{2}$$

where a—end of the period under analysis (8760 h) and Δt_k—duration of a constant load value (1 h).

The operation of an energy system that includes energy storage is shown schematically in Figure 6a–d. Figure 6a shows power demand P_D in the selected period and available power P_G of the sources installed in the system at that time. If there is an excess of available power, which in Figure 6 occurs in periods $t_0 \rightarrow t_1$, $t_2 \rightarrow t_3$, $t_4 \rightarrow t_5$, the power is used for charging the energy storage facilities. This process is illustrated in Figure 6b, which shows the state of the storage charge C_S. In turn, Figure 6c shows the periods when power is drawn from the system to charge the storage. In periods $t_1 \rightarrow t_2$ and $t_3 \rightarrow t_4$, the power demand exceeds the system's available power and then the shortage can, at least partially, be compensated for from the energy storage. This is shown in the diagram in Figure 6b,c. In periods $t_1 \rightarrow t_1'$ and $t_3 \rightarrow t_4$, energy storage supports the system, discharging with power

P_L. Figure 6b indicates that in period $t_1 \rightarrow t_1'$ the storage was fully discharged, while in period $t_3 \rightarrow t_4$ the storage facilities giving power to the system still had some energy left.

An energy system configured in this way can provide the required level of reliability, assuming that

- There are enough power sources installed in the system to make sure that the excess power can be used to charge storage systems during periods of lower energy demand;
- The system storage facilities have sufficient capacities to store the excess energy available in certain periods of the system operation, and they are able to return this power to the system in the case of shortage.

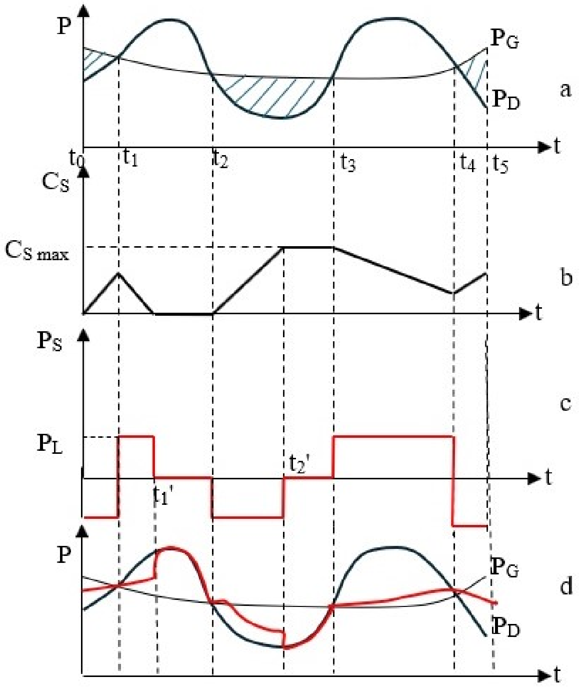

Figure 6. Diagram illustrating the system's demand for power and its generation capability (**a**), storage operation (**b**,**c**), and adjusted demand for power (**d**).

In further analyses, it is assumed that the energy drawn from the storage during the discharging phase reduces the power demand by the values of the power of the storage facilities being discharged, which are shown in Figure 6d in periods $t_1 \rightarrow t_1'$ and $t_3 \rightarrow t_4$. At the same time, the charging of the storage facilities increases the power demand in the system in periods $t_0 \rightarrow t_1$, $t_2 \rightarrow t_2'$, and $t_4 \rightarrow t_5$ (Figure 6d). The above conditions of the energy system operation are satisfied provided that adequate storage capacity and adequate charging/discharging power of the storage are ensured. The task of selecting appropriate storage parameters that could ensure reliable operation of the Polish energy system was formulated in the following way: for the assumed structure of the power sources in the system and the assumed power demand characteristic in a given year, the optimal capacity of energy storage facilities C_{Smax} and their optimal power P_L were selected so that the said energy system supported by such storage should ensure the required reliability of energy supplies. This required level of reliability is adopted in further analyses as the LOLE limit value of 3 h/year.

5. Current State and Planned Evolution of the Energy System

The starting point in the procedure for selecting the optimal structure of the energy system in the coming years is the current system structure, the current demand for power, and the expected change in this demand in the future. The structure of the sources in the Polish energy system in 2023 and planned in 2035 and 2040 is shown in Figure 7 and in Table 1.

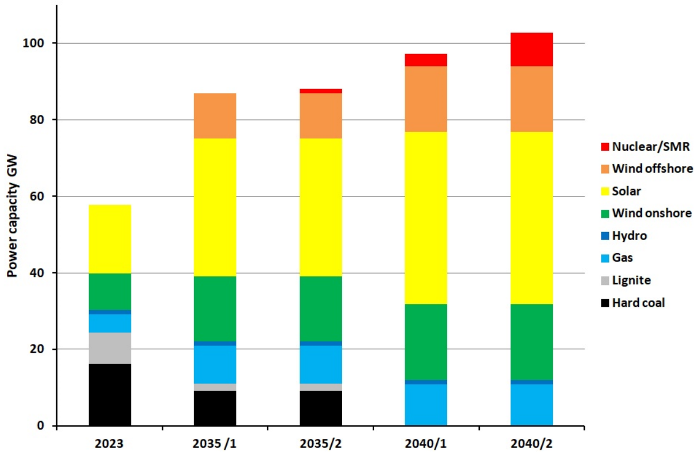

Figure 7. Current and planned structure of power sources in the energy system.

Table 1. The structure of the sources in the Polish energy system.

Power Capacity [GW]					
Year	**2023**	**2035/1**	**2035/2**	**2040/1**	**2040/2**
Hard coal	16.11	9.13	9.13	0	0
Lignite	8.23	1.8	1.8	0	0
Gas	4.7	10	10	10.8	10.8
Hydro	1.2	1.2	1.2	1.2	1.2
Wind onshore	9.5	16.94	16.94	19.8	19.8
Solar	18	36	36	45	45
Wind offshore	0	11.88	11.88	17.2	17.2
Nuclear/SMR	0	0	1.12	3.3	8.8
Total	57.74	86.95	88.07	97.3	102.8

In 2023, the Polish energy system had coal-fired units with a total capacity of 24.34 GW, wind sources with a capacity of 9.5 GW, PV sources with a capacity of 18 GW, and gas-fired units with a total capacity of 4.7 GW. According to the plans, in 2035 coal-fired sources with a capacity of 10.93 GW will remain in the system, the capacity of onshore wind sources will increase to almost 17 GW and offshore to almost 12 GW, and the capacity of gas-fired units will also increase to 10 GW and perhaps the first nuclear unit will appear.

In 2040, the Polish system will no longer be planning to produce energy from coal-fired units; their role should be taken over by subsequent nuclear units and renewable energy sources with a total capacity of over 82 GW.

The hourly power demand in 2023 is shown in Figure 8. The ordered graph of the power demand is marked in red. The above data, supplemented with the information on the failure rate of individual types of energy sources, made it possible to calculate the cumulative distribution function of the system power in 2023, with PV sources (day) and without them (night) (cf. Figure 9).

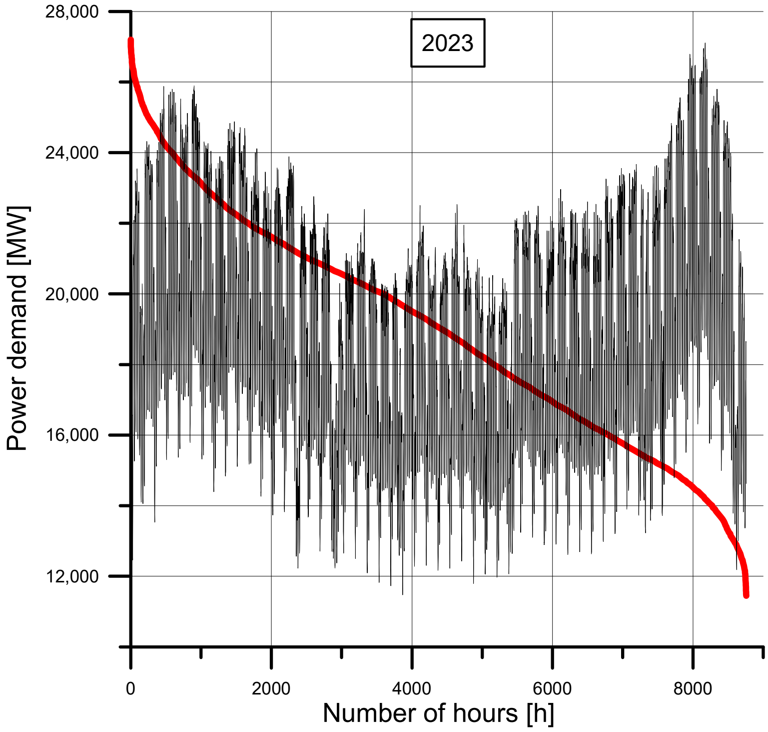

Figure 8. Demand for power in 2023.

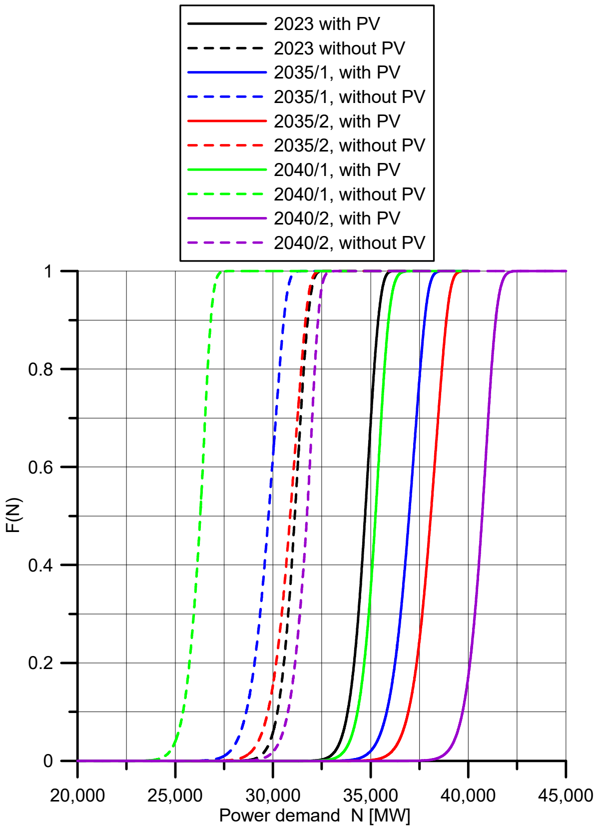

Figure 9. Cumulative distribution function of available power for the system structure in 2023 and for two variants of the system structure in 2035 and 2040.

According to the changes planned in the Polish energy system discussed in various forecasts [44,45], the structure of the system in 2035 and in 2040 may look as shown in

Figure 7. The significant changes compared to the current state are a drastic reduction in coal sources and an increase in power obtained from renewable energy sources. At the same time, there will be a substantial change in the demand for electricity due to the planned universal electrification of many sectors of the economy, especially heating and transport. Two variants of changes in energy demand in 2035 and in 2040 were considered in further analyses. They are shown in Figure 10 in the form of ordered graphs.

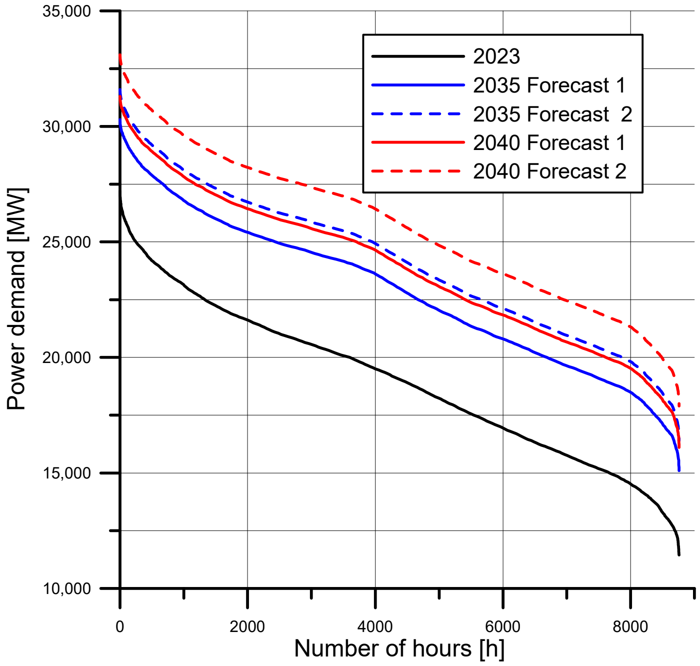

Figure 10. Power demand in 2023 and forecast for the demand in 2035 and 2040.

The above data, i.e., the predicted structure of the national energy system and the expected power demand, made it possible to calculate the cumulative distribution function of the system power, together with the LOLP and the LOLE indices in the analyzed period (cf. Table 2).

Table 2. LOLP for different forecasts and systems.

Year		2023	2035 Forecast 1	2035 Forecast 2	2040 Forecast 1	2040 Forecast 2
Peak power demand [MW]		27,106	30,259	31,575	31,284	33,075
				LOLP [%]		
System 2023	With PV	2.3×10^{-12}	4.1×10^{-5}	9.8×10^{-3}	3.2×10^{-3}	1.48
	Without PV	2.8×10^{-4}	10.69	79.88	61.34	100
System 2035/1	With PV	5.4×10^{-13}	8.4×10^{-7}	1.1×10^{-4}	4.0×10^{-5}	0.014
	Without PV	0.39	76.01	99.99	99.96	100
System 2035/2	With PV	0	8.7×10^{-9}	2.0×10^{-6}	6.2×10^{-7}	4.4×10^{-4}
	Without PV	0.02	23.02	86.18	71.55	100
System 2040/1	With PV	1.0×10^{-11}	2.1×10^{-5}	3.2×10^{-3}	1.1×10^{-3}	0.41
	Without PV	98.43	100	100	100	100
System 2040/2	With PV	0	3.0×10^{-14}	1.2×10^{-11}	3.3×10^{-12}	7.0×10^{-9}
	Without PV	3.7×10^{-4}	3.37	39.98	25.98	99.98

For the first forecast and a system without PV sources, i.e., for the system operation during the night, the LOLP index is 10% and the LOLE index is 56.6 h. For the second forecast, predicting higher energy demand, the values are as follows: LOLP = 80%, LOLE = 184 h. This means that the presented system structure does not ensure the required level of reliability of electricity supplies to customers at all times of the day or night. In the next section, the possibility of the energy system achieving the required reliability through the use of energy storage is considered.

6. Selection of Required Energy Storage Parameters

The planned structure of the energy system and the planned demand for energy presented in the previous section indicate that the system will be unable to achieve a satisfactory level of energy supply reliability. Due to the large number of renewable sources in the system, there are periods of a significant excess of power compared to the real power demand. Therefore, an analysis was performed of the possibility of using periods with excess power in the system to charge the energy storage facilities, which will then make it possible to meet the increased demand for power. As described in Section 4, the required capacity of the storage facilities and their required discharge power were sought to ensure the value of the LOLE parameter of 3 h. The results of the selection of the storage parameters are shown in Figure 11.

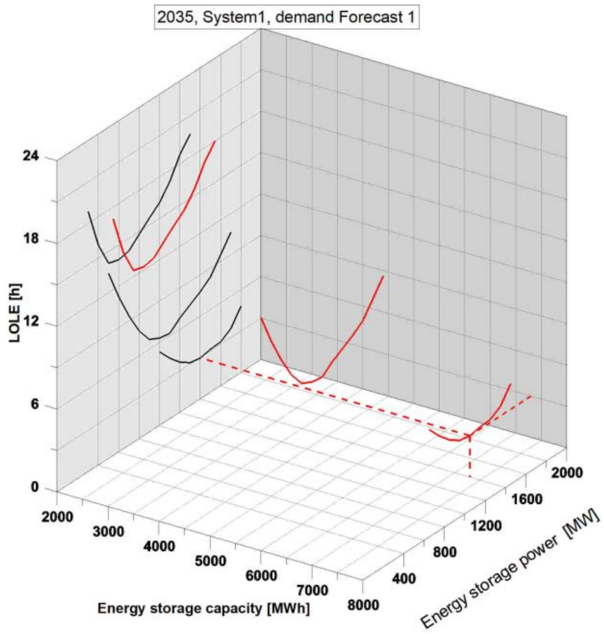

Figure 11. LOLE depending on the energy storage capacity and power for the forecast of power demand in 2035 (red lines), and their projection on the plane LOLE—storage power (black lines).

The curves drawn in red show the dependence of the LOLE index on the storage power for selected values of the storage capacity. The projection of these curves on the plane LOLE index—the storage power—is marked in black. The expected requirements, i.e., the values of the system's LOLE index are lower than 3 h, are met by storage facilities with the total capacity of 7.3 GWh and the total discharge power of 1.4 GW. The operation of the system with storage facilities for one selected week is illustrated in Figure 12. The initial power demand is marked in red (Figure 12a). The change in the demand resulting from the energy storage operation is marked in blue. The storage charging and discharging periods are shown in Figure 12b.

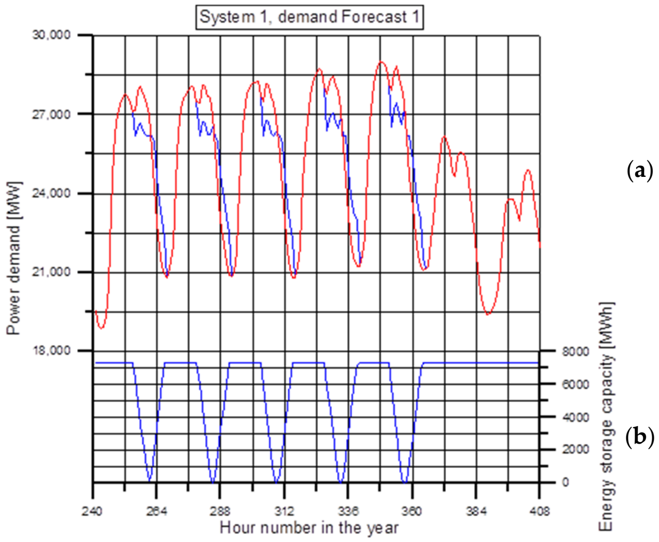

Figure 12. System operation supported by energy storage facilities, (**a**) power demand, red line—initial power demand, blue line—final power demand with consideration of energy storage, (**b**) energy storage capacity.

The presented results of the selection of the energy storage facilities supplementing the energy system structure relate to the first forecast of the energy demand in 2035. Also examined was the possibility of using energy storage to ensure the system reliability at increased power demand, described in Figure 10 as Forecast 2. The results of the selection of the storage parameters are shown in Figure 13.

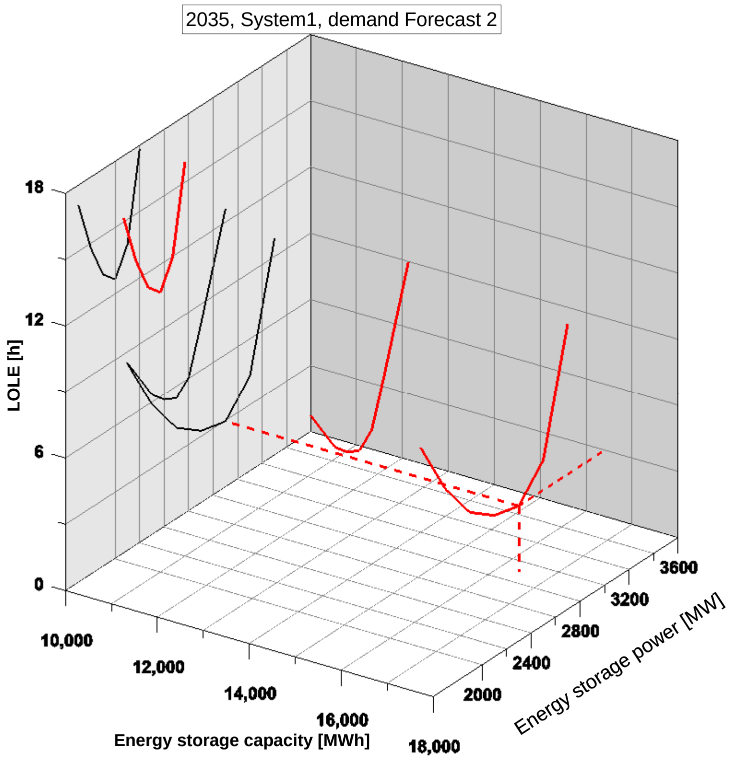

Figure 13. LOLE depending on the energy storage capacity and power for Forecast 2 of the power demand in 2035 (red lines), and their projection on the plane LOLE—storage power (black lines).

Under these conditions, maintaining the required values of the LOLE index would require storage facilities with a total capacity of 16.4 GWh and a total power of 2.9 GW, which seems difficult in practice. Therefore, the possibility of supplementing the system structure with other stable energy sources was considered. The incorporation of a few nuclear units into the system was considered in detail. The calculation results for a system modified in this way and supplemented with a 1.2 GW nuclear power unit are shown in Figure 14.

Supplementing the system with energy storage with a total capacity of 8.7 GWh and a total power of 1.6 GW enables the system to achieve the required level of reliability of electricity supplies at increased demand for energy and power, described as Forecast 2 in Figure 10.

The year 2040 was assumed as the target year for full decarbonization of the Polish energy system. The possibility of achieving this goal was checked for structure system 1, as shown in Figure 7, i.e., with nuclear sources with a capacity of 3.3 GW. Considering the demand Forecast 1 (Figure 10), the possibility of balancing the system was achieved by installing storage facilities with a total capacity of 220 GWh, which is an unrealistic value in Polish conditions. Therefore, the second variant of the system structure for 2040 was considered, also without coal units but with nuclear units with a capacity of 8.8 GW (Figure 7). Such a system will provide an appropriate level of reliability for the energy demand in 2040 described as Forecast 1, even without the need to install additional energy storage facilities. For the increased demand described as Forecast 2, the system will ensure maintenance of the required reliability parameters, i.e., a LOLE value of 3 h if energy storage facilities with a total power of 2 GW and a capacity of 11.1 GWh are installed (Figure 15).

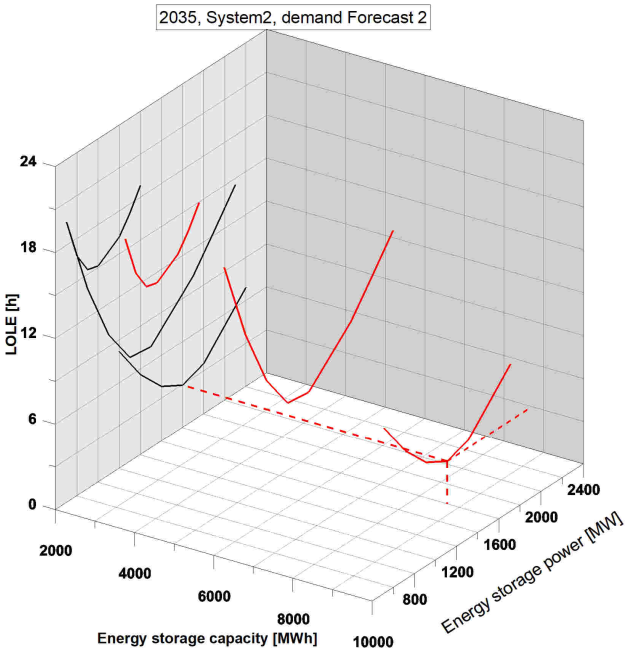

Figure 14. LOLE depending on the energy storage capacity and power for the power demand according to Forecast 2 in 2035 and a system with nuclear units (red lines), and their projection on the plane LOLE—storage power (black lines).

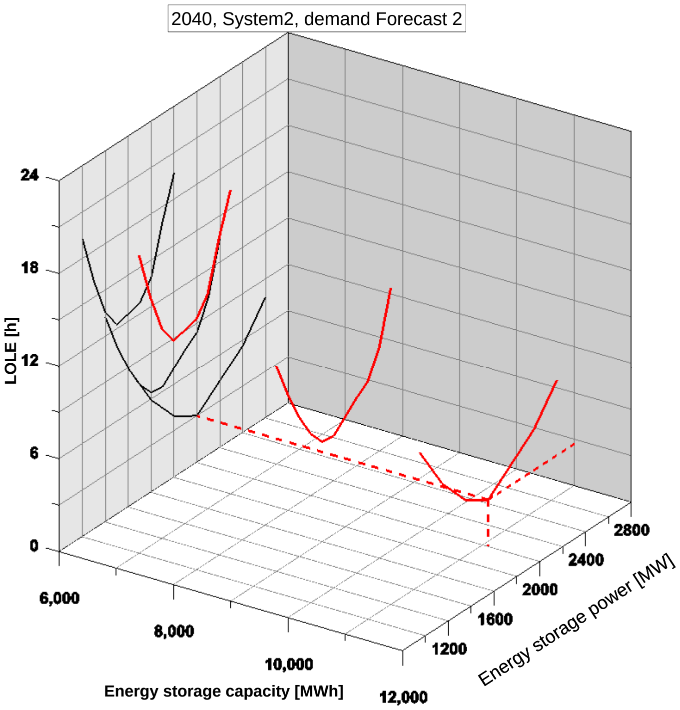

Figure 15. LOLE depending on the energy storage capacity and power for the power demand according to Forecast 2 in 2040 and a system with nuclear units (red lines), and their projection on the plane LOLE—storage power (black lines).

The LOLP and LOLE indices were used, among others, in [43] to assess the reliability of a change in the structure of a certain energy system. This change consisted in replacing a nuclear unit with a capacity of 696 MW with three wind turbines with a total capacity of 3480 MW. Based on the calculated values of the LOLE and LOLP indices, it was shown that such a replacement would worsen the reliability of this system.

7. Summary

The structures of the energy systems in most European countries, including Poland, have undergone significant changes in recent years resulting from the implementation of the decarbonization policy of the energy production sector. Difficulties in implementing this process are related to the different structures of the energy system of a given country. In the case of Poland, with a large share of energy production from coal and no nuclear power plants, changing the structure of the energy system is particularly difficult and requires caution in planning the decommissioning of subsequent coal units. The overriding criterion that must be taken into account is ensuring the reliability of energy supplies to all recipients. A comparison of the pace of introducing renewable energy sources into the energy system in Poland and other EU countries indicates that in the case of Poland, this pace is much higher than the average pace in the entire EU. However, maintaining the energy system reliability at an appropriate level requires broader action. The first possibility, which was considered in this paper, is the use of energy storage in periods in which the system generates power in excess compared to demand. The stored energy would be used to cover possible shortages due to power demand in peak hours. The results of the analyses indicate that at a moderate increase in the demand for electricity and power anticipated for 2035, the structure of the power sources in a system with a high share of wind and solar energy may be sufficient if the system makes use of energy storage facilities with a total capacity of at least 7.3 GWh and 1.4 GW of power. Such storage parameters can be obtained in the Polish energy system, e.g., as pumped-storage power plants. At the increased demand described in Figure 10 as 2035 Forecast 2, it would be necessary to double the storage capacity to 16.4 GWh and increase its power to about 3 GW. In this situation, it would be more rational to use additional stable sources of energy in the system in the form of nuclear power units or SMR nuclear units. To balance the system at increased power demand, one 1.12 GW nuclear power unit should be added to the system.

In 2040, a system without coal units but with three nuclear units with a total capacity of 3.3 GW would require support from storage facilities with unrealistic capacities to balance the demand expressed in Forecast 1. This demand could be balanced by additional nuclear units with a total capacity of 8.8 GW. In the event of increased demand for power according to the 2040 Forecast 2, the energy system, in addition to the planned RES sources and the above-mentioned nuclear units, would require support from storage facilities with a total capacity of at least 11.1 GWh and a total power of 2 GW. The values given above indicate the theoretical possibilities of decommissioning coal units by 2040 with the inclusion of nuclear units with a capacity of at least 8.8 GW in the system and supporting the operation of renewable sources by storage facilities with the above-mentioned capacities. The flexible operation of such a system must also be supported by gas units with a total capacity of over 10 GW.

The decarbonization of the Polish energy system and, more broadly, of our entire economy is a process that is taking place with increasing intensity. Such actions are provided for in the official plans of the ministries and agencies of the Polish government [44]. By 2030, total expenditure on the transformation of the Polish energy system and the construction of new emission-free energy sources is to reach PLN 800 billion [45].

It is also important that Poland has already managed to significantly reduce carbon dioxide emissions from various sectors of the economy. According to data included in [46], total CO_2 emissions in Poland decreased in 2023 to 152 million tons, while in 2022 they amounted to over 184 million tons. This means a year-on-year decrease in emissions of approx. 20%.

The above-mentioned reduction in CO_2 emissions was achieved in many industries not only by implementing low-emission technologies in these areas; above all, it was a consequence of closing down production in these sectors in Poland and moving it to other countries. For this reason, unfortunately, it is not a factor stimulating economic growth.

Energy storage can play an important role in increasing the reliability of the Polish energy system. Section 2 discusses existing and planned energy storage systems. In reality, in Poland, these can be pumped-storage or battery storage systems. At present, the most advanced project is the construction of the Młoty pumped-storage power plant, whose power can be increased from 750 MW to 1050 MW, and the cost of its construction is planned at approx. PLN 5 billion.

In turn, Polska Grupa Energetyczna (PGE) is building a large-scale battery storage system in Żarnowiec with a power of 262 MW and a capacity of 981 MWh, and its cost exceeds PLN 1.5 billion. PGE plans to build further energy storage systems with a capacity of 17 GWh by 2035, and the value of these investments is estimated at PLN 18 billion [47].

In the face of the very high costs of transforming the Polish energy system, international exchange will play an important role in ensuring the reliability of energy supplies. The Polish energy system is connected to the systems of neighboring countries, i.e., the German, Czech, Slovak, Lithuanian, Ukrainian, and Swedish systems. Further development and optimization of the cooperation of these systems should increase both energy security in Europe and reduce costs. This issue will be the subject of further analyses.

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draft preparation, A.R. and A.W.; review and editing, A.R. and A.W.; supervision, A.R. All authors have read and agreed to the published version of the manuscript.

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