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Energy Storage Potential Needed at the National Grid Scale (Poland) in Order to Stabilize Daily Electricity Production from Fossil Fuels and Nuclear Power

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Abstract: With the increasing share of renewable sources in the energy mix, there is a need to balance energy production from weather-dependent sources, such as wind turbines and photovoltaics. This is also a current global trend associated with climate policy. In Poland, there has been a significant increase in energy production from renewable sources, leading to a duck curve phenomenon mainly in the case of photovoltaics, which requires balancing this production through various measures. One possible way to achieve this is energy storage installation. This article identifies the need for energy storage to ensure the stability of electricity production from low-flexibility sources like coal-based power plants. For this purpose, a methodology has been developed to determine the daily minimum energy storage capacities which would also allow for the integration of other stable (though less flexible) energy sources, such as nuclear power. In the case of Poland, energy storage has been estimated to require, as a median value, approximately 6 GWh of additional storage capacity, which is equivalent to twice the planned capacity of the Młoty Pumped Storage Power Plant.

Keywords: PSH; energy storage; Poland; intermittent energy source; RES; nuclear power; fuel saver sources; duck curve; energy transition; photovoltaic; wind turbine

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1. Introduction

In recent times, Poland has experienced a dynamic increase in the installed capacity of renewable energy sources, especially in photovoltaics [1–3], along with changes in the profile of electricity demand [4,5], also caused by the pandemic and post-pandemic situation [6,7]. The year-on-year growth in energy production from unstable sources such as wind and PV is depicted in Figure 1. There is also a decrease in the demand for energy production from fossil fuel sources due to the implementation of fuel-saving sources in Poland in the last 2–3 years, primarily photovoltaics [8,9]. At the same time, local community energy based on energy virtualization [10] and energy communities [11] is developing strongly. In the literature, more and more research is being conducted on the energy transformation of Poland, whose energy profile is changing [8] due to the search for alternatives to emission-intensive mining [12,13]. Renewable sources such as photovoltaics [3,14] and partly hydrogen energy [15–18] are becoming more and more popular [19]. Another promising direction is energy storage [20,21].

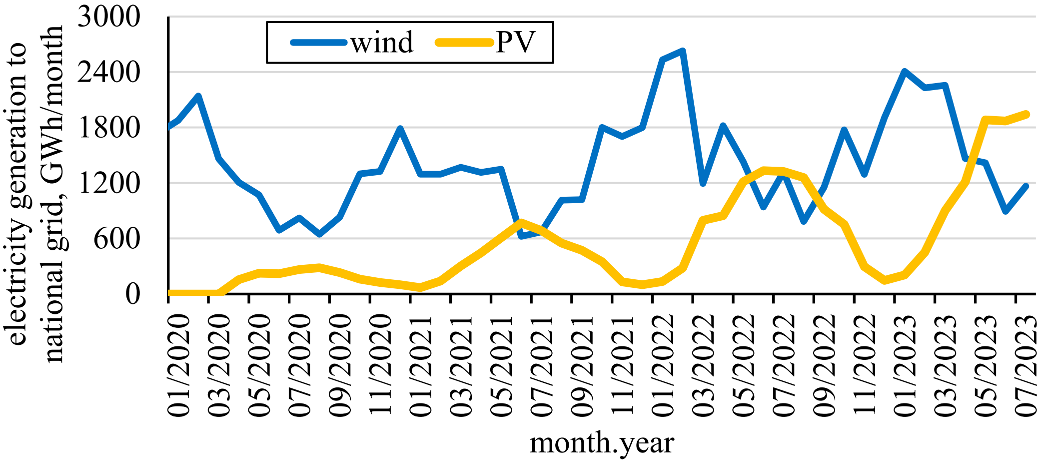

Figure 1. Monthly electricity production from wind turbines and photovoltaics in Poland 2020–April 2023. Source: own study based on [22].

The maximum monthly energy production values (year-scale) from wind turbines between 2020 and 2023 ranged from 2100 to 2650 GWh and occurred during winter months, whereas the maximum monthly energy production values from photovoltaics increased from less than 300 GWh/month in 2020 to around 1300 GWh/month in 2022 (July). With the growing installed capacity, it is estimated that these values will be higher in 2023 and subsequent years. However, especially on weekends, significant surplus energy is generated from photovoltaics or wind sources [7,23,24]. As a result, there is a need to manage the surplus electricity generation from renewable energy sources [25,26].

The consequence of increasing photovoltaic energy production is the emergence of a phenomenon called the duck curve [27]. An analysis of the impact of the duck curve in Poland was conducted by Olczak et al. [28], although the analysis focused on the initial phase of installed capacity development in photovoltaics. Some methods to mitigate the duck curve include designated energy zones [29,30], demand-side response [31], and the use of dynamic electricity tariffs, which can help reduce imbalances in electricity production from base load power sources in the power system [32]. This is particularly important in the context of plans for constructing a nuclear power plant in Poland [33], which will have low controllability.

An alternative to energy storage comes in the form of making conventional power plants more flexible [34,35], but most Polish power plants are old (more than 30 years of age).

Thus far, there has been no analysis on the magnitude and potential contribution of energy storage systems in decreasing the production of energy from stable sources (with low flexibility), such as fossil fuels (mainly hard coal and lignite in Poland [8,36,37]). The main novelty of this article is the development of a methodology for determining the energy storage needs at the national/country level to balance the unevenness in energy production from renewable sources, considering the variability in energy demand and the existing mechanisms of market balancing through pumped hydro storage power plants. This article is structured as follows: Section 2 describes the materials and methods, Sections 3 and 4 summarize the results and discussion, and finally, Section 5 provides the conclusions.

2. Materials and Methods

The calculation methods used in this study were intended to demonstrate the needs for energy storage at the scale of the entire energy system in Poland. The data for the analysis were obtained from January to May 2023 from the PSE website [22,38] in the following format:

- Hourly gross energy generation (*GEG*), in GWh;
- Hourly energy production from coal sources: coal energy generation (*CEG*), in GWh;

- Hourly energy production from wind sources: wind energy generation (*WEG*), in GWh;
- Hourly energy production from photovoltaic sources: photovoltaic energy generation (*PVEG*), in GWh.

For each day of the year, the differences (in terms of range and deviations) in the production of energy from low-flexibility sources, namely hard coal and lignite, were determined. The obtained data consider the influence of the entire market, including the balance with existing pumped storage power plants. To do so, the following calculations were performed: determining the average daily production values and deviations, and then estimating the energy storage capacity based on them.

The average amount of energy produced from hard coal and lignite sources on a daily scale was determined using the following formula:

$$mCEG(day) = \frac{\sum_\tau CEG(day,\tau)}{24} \tag{1}$$

where

$mCEG$: daily mean hourly values of hard coal and lignite electricity production and coal energy generation, in GWh;
CEG: hourly value of coal energy generation—data retrieved from PSE website [38], in GWh;
day: day in the year 2023,
τ: hour of the day: 1. . .24.

The average amount of energy produced from all sources daily was determined using the following formula:

$$mGEG(day) = \frac{\sum_\tau GEG(day,\tau)}{24} \tag{2}$$

where

$mGEG$: daily mean hourly values of total electricity production: gross energy generation, in GWh;
GEG: hourly value of total electricity production (gross energy generation)—data retrieved from PSE website, in GWh.

Then, the differences in the hourly value in relation to the average value in the generation of energy from sources powered by hard coal and lignite (Equation (3)) and between individual days (Equation (4)) were determined:

$$dmCEG(day,\tau) = mCEG(day) - CEG(day,\tau) \tag{3}$$

where $dmCEG$: difference between mean at the daily scale and hourly values of coal energy generation, in GWh.

$$ddmCEG(day) = mCEG(day) - mCEG(day-1) \quad if\ day > 1 \tag{4}$$

where $ddmCEG$: daily difference between mean CEG values ($mCEG$), in GWh.

The daily value of the hourly production from hard coal and lignite sources was determined using the following formula:

$$rCEG(day) = \max(CEG(day,\tau)) - \min(CEG(day,\tau)) \tag{5}$$

where $rCEG$: range of daily maximum and minimum values of CEG, in GWh.

On the other hand, the daily value of the hourly range of production from hard coal and lignite sources as a percentage was determined using the following formula:

$$prCEG(day) = \frac{\max(CEG(day,\tau))}{\min(CEG(day,\tau))} \times 100\% \tag{6}$$

where *prCEG*: percentage range of daily maximum and minimum values of *CEG*, in GWh.

Half of the daily sum of the absolute values from *dmCEG* determined using Equation (3) is the size of the storage facility required to allow a constant value of energy production from hard coal and lignite sources in one day.

$$CNS(day) = \sum_{\tau} \frac{|dmCEG(day,\tau)|}{2} \quad (7)$$

where *CNS*: capacity (energy storage) needed to reach daily stabilization, in GWh.

The above methodology does not take into account the flexibility of coal or nuclear energy sources on an hourly basis. Therefore, the corrected *CNS* value (*CNSp*) is calculated below, considering the possibility of elasticity in energy production, as indicated by the *d*% value, which enables calculation according to the following two formulas. The following is a simulation of the hourly flexibility of coal or nuclear power plants.

$$dmCEGp(day,\tau,d\%) = \begin{cases} mCEG(day) \times (1-d\%) - CEG(day,\tau) & if\ CEG(day,\tau) < mCEG(day) \times (1-d\%) \\ CEG(day,\tau) - mCEG(day) \times (1+d\%) & if\ CEG(day,\tau) > mCEG(day) \times (1+d\%) \\ 0\ if\ others & \end{cases} \quad (8)$$

where

dmCEGp: difference between mean and hourly values at the daily scale (energy storage) assuming different percentages of elasticity (hourly values of deviations from the daily mean value) *d*%, in GWh.

d%: we assume different percentages of elasticity (hourly values of deviations from the daily mean value) typically range from 0% to 10%.

$$CNSp(day,d\%) = \sum_{\tau} \frac{dmCEGp(day,\tau,d\%)}{2} \quad (9)$$

where *CNSp*: capacity (energy storage) needed to reach daily stabilization considering the possibility of percentage differences, in GWh.

3. Results

Based on Equation (1), the average daily hourly values of energy production were determined, as shown in Figure 2a. On the basis of Equation (3), the differences between the daily average *ddmCEG* were determined; see Figure 2b.

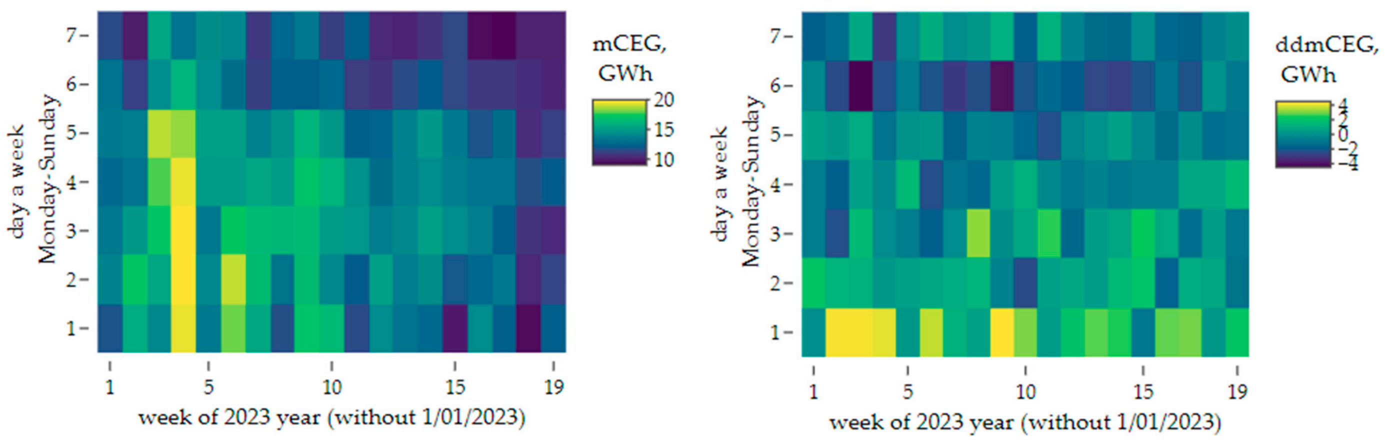

Figure 2. (**a**) Mean daily hourly production of energy from coal power plants, in *mCEG* (GWh per h); (**b**) differences in mean daily hourly production values calculated day-to-day, in *ddmCEG*; Poland, 2 January 2023–14 May 2023. Source: own study.

The influence of the holiday period in the first week of 2023 is noticeable, and the electricity production values were noticeably lower in April and May compared to January and February. It is also obvious that production was significantly lower on weekends. It follows that the greatest differences in the day-to-day comparative scale in the positive values are observable on Mondays (Figure 2b), and the greatest differences in the negative values on Saturdays. This is due to the general differences in energy demand on workdays and weekend days.

The values on a daily scale (mainly based on Equations (1), (2), (5), and (6)) are summarized on the time axis, and the results are presented in Figure 3.

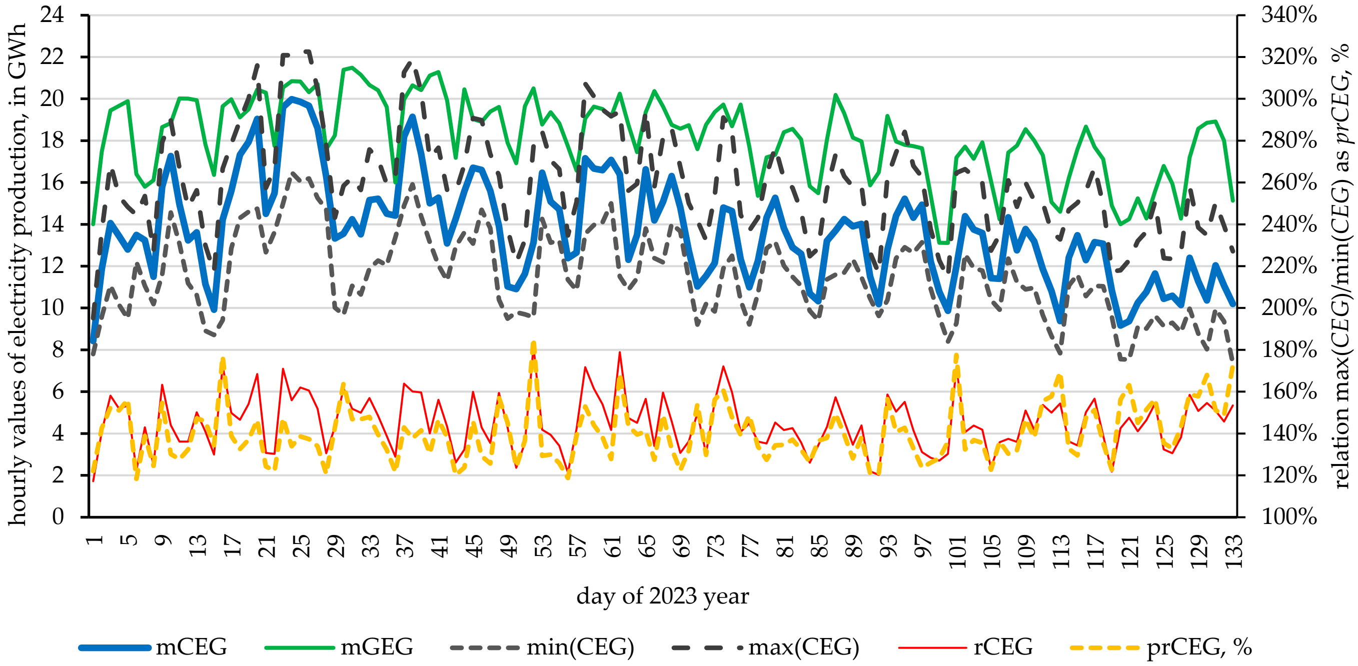

Figure 3. Summary of data on average daily hourly values of energy production (GWh per h), Poland, 1 January 2023–14 May 2023. Source: own study.

The *mCEG* values presented in Figure 2a are shown in Figure 3 in the form of a time series against the background of the mean gross electricity generation (*mGEG*) and the maximum differences between the minimum and maximum values of hourly energy production, from approx. 2 GWh to approx. 8 GWh. This range indicates the need for additional capacity for daily balancing in the range of 2 to 8 GW in balancing sources (flexible, e.g., gas-fired [39] or energy storage). This is not a problem, but the higher the value and more frequent the changes, the higher the failure rate of the electricity generation infrastructure and the lower the efficiency. The largest difference in the power needed to achieve balance, expressed as a percentage, is approx. 80% in relation to the minimum daily production (power demand). This need for flexibility resulted in the creation of a capacity market in Poland [40,41].

The most favorable day was the one with the smallest total deviations from the average value of energy production—1 January 2023 (Figure 4).

On the other hand, the most unfavorable day in 2023 (for the functioning of stable energy sources) was February 21 (Figure 5) due to the occurrence of an evening peak and a more than twofold decrease in the amount of energy generated by wind turbines in the evening compared to around noon.

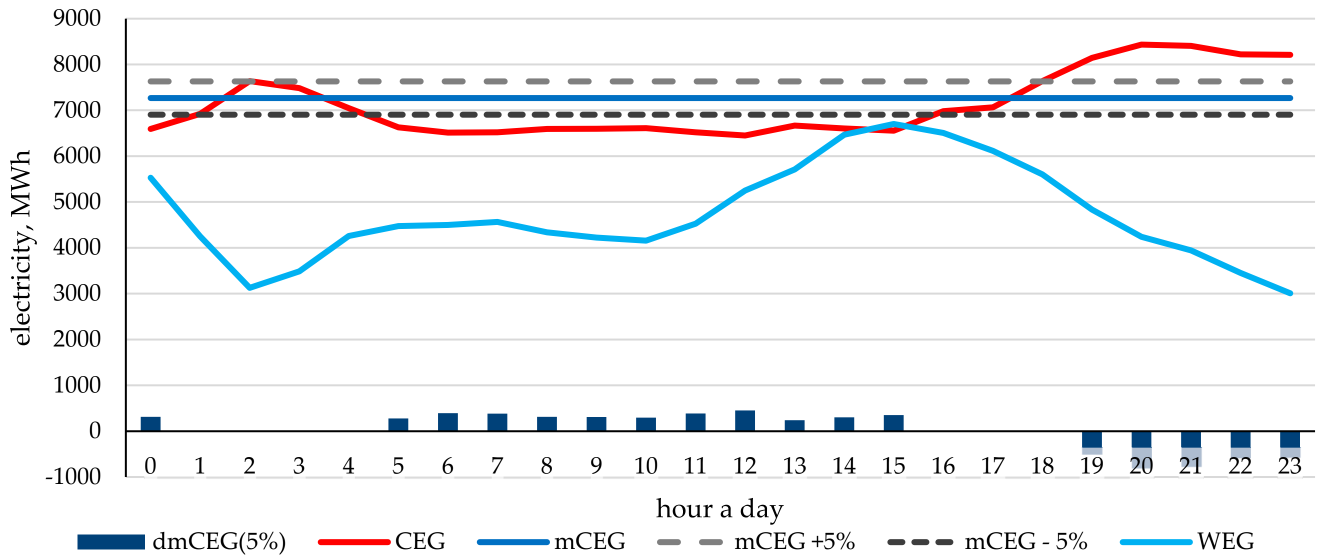

Figure 4. Average daily hourly values and hourly values of electricity production from coal (*CEG*) and wind (*WEG*) sources (GWh per h); deviations in production values from the average daily value with an acceptable deviation of 5% (*dmCEG*(5%)). Poland, 1 January 2023. Source: own study.

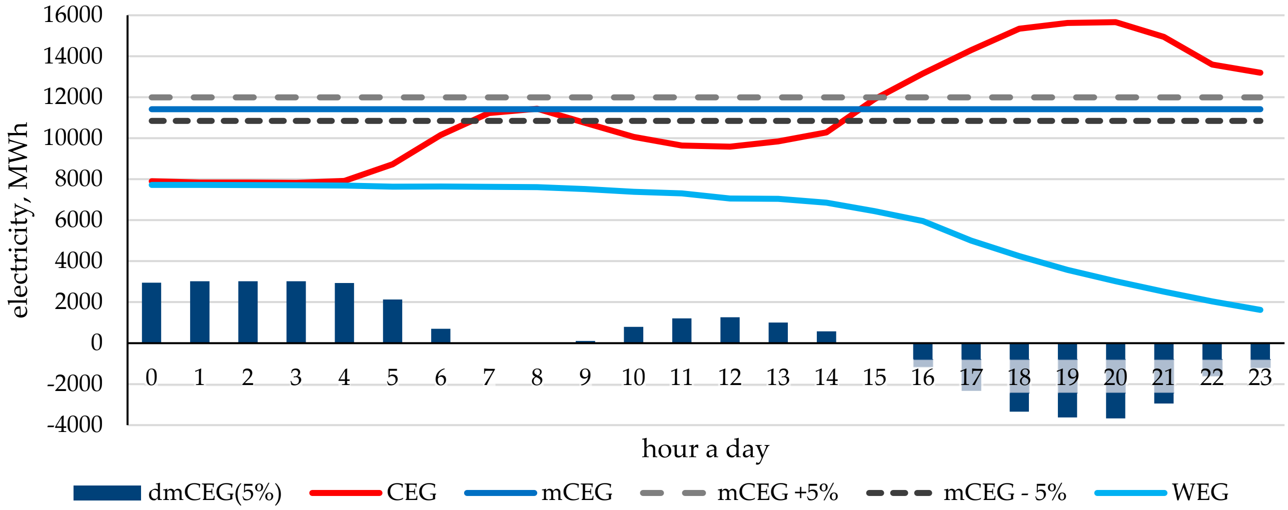

Figure 5. Average daily hourly values and hourly values of electricity production from coal (*CEG*) and wind (*WEG*) sources (GWh per h); deviations in production values from the average daily value with an acceptable deviation of 5% (*dmCEG*(5%)). Data for the day with the highest storage capacity requirement, corresponding to the most unfavorable conditions. Poland, 21 February 2023. Source: own study.

On 21 February 2023, the production of energy from hard coal and lignite sources increased from about 8 GWh to about 15.5 GWh. An energy storage with a capacity of approximately 20 GWh would allow for a constant hourly energy production of 11.4 GWh. In this case, before 6 am and between 10 a.m. and 2 p.m., the energy storage battery would be charged and discharged from 4 p.m., with a maximum peak at 8 p.m.

Figure 6 shows the calculation results for a day with a high share of energy production from photovoltaics. In this case, between 9 am and 3 p.m., the energy storage battery was charged and discharged from 6 p.m., with a maximum peak at 8 p.m. The battery was charged up to a maximum of 2.1 GWh at 11 a.m. when the *PVEG* value was higher than 7 GWh.

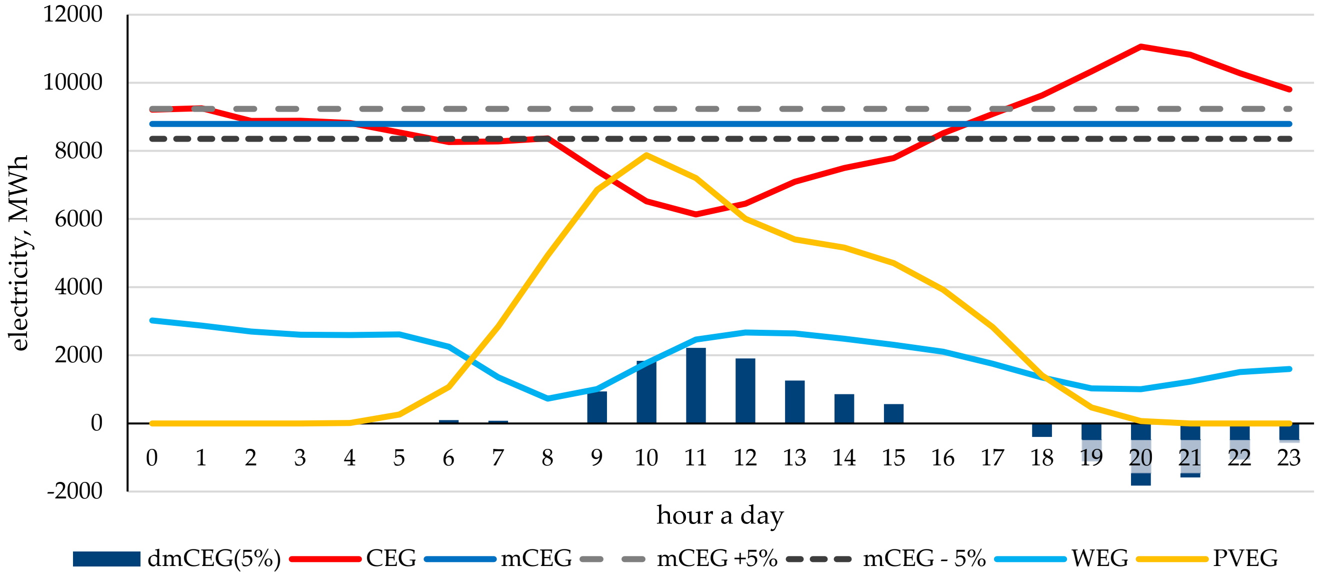

Figure 6. Average daily hourly values and hourly values of electricity production from coal (*CEG*), wind (*WEG*), and photovoltaic (*PVEG*) sources (GWh per h); deviations in production values from the average daily value with an acceptable deviation of 5% (*dmCEG*(5%)). Data for a day with a high value of PV energy production (61 GWh/day). Poland, 13/05/2023. Source: own study.

The cumulative amount of energy required for storage (*CNS*) to achieve consistent daily energy production levels is presented in Figure 7. Additionally, the daily energy production from photovoltaic systems (*PVEG*) and wind turbines (*WEG*) is shown.

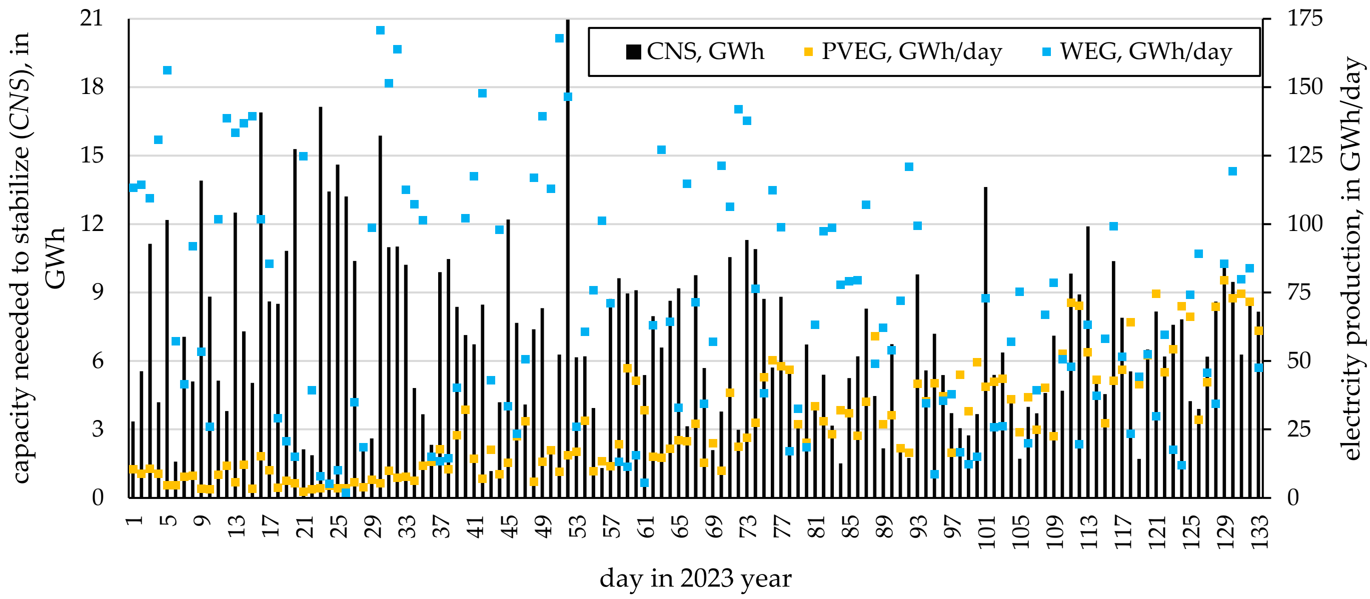

Figure 7. Capacity needed to stabilize electricity production in 2023 as well as photovoltaic energy, *PVEG*, and wind turbine energy, *WEG*, in Poland, 1 January 2023—14 May 2023. Source: own study.

In the first 80 days of 2023, higher energy production from wind turbines was noticeable, which was associated with higher *CNS* values than the following days. The high value of *CNS* (>6 GWh) was caused by a high *WEG* value (>70 GWh/day) or high *PVEG* value (>50 GWh/day). An analysis of the graph (Figure 7) shows the low impact of photovoltaic sources on high *CNS* values so far. *CNS* values, sorted from highest to lowest, are shown in Figure 8.

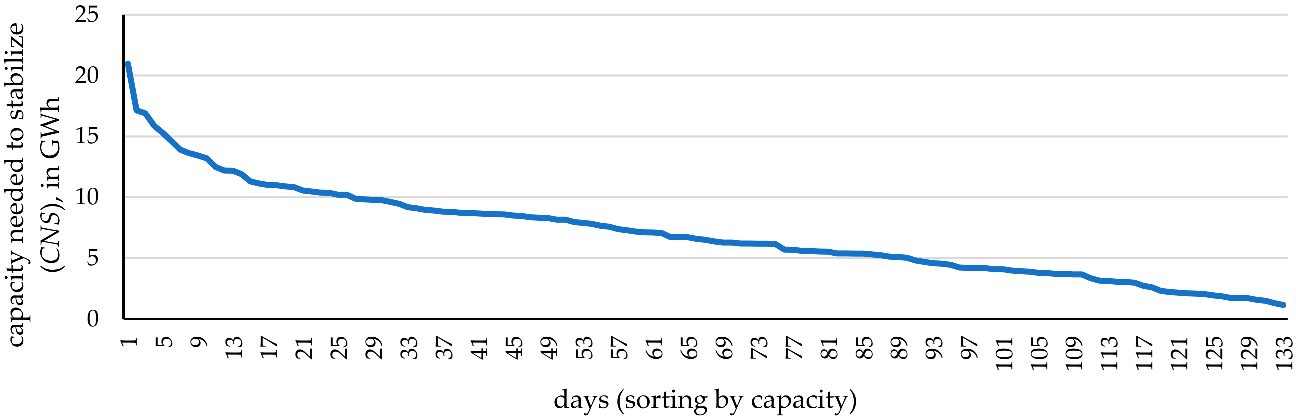

Figure 8. Capacity needed to stabilize electricity production (by capacity) sorted by day in Poland, 1 January 2023–14 May 2023. Source: own study.

The maximum capacity of the storage facilities needed to stabilize the energy was over 20 GWh (to cover the most unfavorable day differences in *CEG*). The median was 6.5 GWh, and the smallest value was 1.17 GWh. For more than 20% of the days, the requirements of the stabilization process exceeded 10 GWh of daily storage capacity.

4. Discussion

The conducted analysis pertains to the current (2023) installed power capacities in Poland. However, there are plans in Poland to increase power capacities, especially in the field of photovoltaics and wind turbines, such as those on offshore installations. The noticeably higher impact of wind turbines on the need to increase energy storage capacity may be intensified by the installation of offshore wind turbines [42,43].

Proposed directions for further work are as follows:

- Instead of examining the deviations from the daily average value, study the deviations from a given function, such as a regression function.
- Study different levels of installed capacity for weather-dependent sources, such as wind capacity +50%, PV capacity +50%, and conduct sensitivity analyses [44].
- Investigate the flexibility of fossil fuels and nuclear power sources, including both hourly flexibility and deviations from the desired power level.
- Apply a different energy production stabilization strategy on Mondays and Saturdays due to these days having the largest value fluctuations on a day-to-day basis (Figure 2b).
- Compare obtained results with results in other countries and determination, based on the developed methodology, of changes in the needs of energy storage in recent years.
- Develop a new method for the quantification of the contribution of energy storage to security of supply [45], based on an Indian case study [46].
- Determine the influence of energy demand control on energy storage needs [47].

Other authors have found that the stability of an electricity service mainly depends on two main factors: power plant capacity and possible/real value of electricity imports [48]. Rokicki et al. conducted a study on changes in energy consumption and also energy intensity in all EU countries, finding they had an influence on the need for storage capacity [49,50].

Possible benefiters of the obtained results are as follows:

- Government parties, when determining changes to plans in the field of energy, such as the Polish Energy Policy 2040 [51].
- Investors (of energy storage), when determining the demand for energy storage on the scale of the entire energy system.

- Investors (of renewable energy sources), when energy storage needs in relation to the potential daily value of energy source productivity results in the possibility of exporting energy to the grid and a potential range of electricity prices.
- Investors (of a coal power plant or nuclear power plant), when specifying the size of fluctuations in the daily demand for energy from these types of sources together with the existing energy storage facilities. This affects, e.g., the possibility of equal energy production on a daily basis and the price range for the sold (produced) energy.
- Users, for example, households and consumers of electricity; the greater the demand for energy storage, the greater the potential differences in electricity prices for consumers (e.g., on an hourly basis).

5. Conclusions

This article presents an approach to mitigating the adverse effects of unstable, weather-dependent energy sources on the operation of traditional coal or nuclear power plants (planned in Poland). These stable or baseload electricity sources should not be disconnected and connected to the national grid hourly, but they can be connected and disconnected, for example, once per week, to stabilize their operation (and increase their lifetime) and avoid the costs and barriers associated with frequent shutdowns and startups of power plants.

This analysis aimed to demonstrate the required quantities of energy storage on specific days. The median storage capacity needed was approximately 6.5 GWh. The calculations focused on the year 2023, considering the relatively low share of renewable energy sources, particularly photovoltaics, in previous years up to 2022. Hourly energy production data served as the basis for the analysis, and a methodology for determining daily energy storage requirements was developed. This methodology will be useful in determining the expansion needs of energy storage systems.

One limitation of this research was that we only analyzed daily fluctuations in energy production values, and a significant increase in installed capacity (especially renewable energy) may lead to medium-term energy storage requirements. In addition, changes in the average demand for energy on a daily basis may be balanced by switching the units of traditional power plants on or off or with planned shutdowns of these power plants. High differences (above 48 GWh/day) between the average daily energy production values occur on the border between working days and weekends.

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References

1. Duda, J.; Kusa, R.; Pietruszko, S.; Smol, M.; Suder, M.; Teneta, J.; Wójtowicz, T.; Żdanowicz, T. Development of Roadmap for Photovoltaic Solar Technologies and Market in Poland. *Energies* **2022**, *15*, 174. [CrossRef]
2. Gulkowski, S. Specific Yield Analysis of the Rooftop PV Systems Located in South-Eastern Poland. *Energies* **2022**, *15*, 3666. [CrossRef]
3. Olczak, P.; Żelazna, A.; Stecuła, K.; Matuszewska, D.; Lelek, Ł. Environmental and economic analyses of different size photovoltaic installation in Poland. *Energy Sustain. Dev.* **2022**, *70*, 160–169. [CrossRef]
4. Sawicka-Chudy, P.; Rybak-Wilusz, E.; Sibiński, M.; Pawelek, R.; Cholewa, M.; Kaczor, M. Analysis of possibilities and demand for energy in a public building using a tracking photovoltaic installation. *E3S Web Conf.* **2018**, *49*, 96. [CrossRef]
5. Wróblewski, P.; Niekurzak, M. Assessment of the Possibility of Using Various Types of Renewable Energy Sources Installations in Single-Family Buildings as Part of Saving Final Energy Consumption in Polish Conditions. *Energies* **2022**, *15*, 1329. [CrossRef]
6. Kaczmarzewski, S.; Matuszewska, D.; Sołtysik, M. Analysis of Selected Service Industries in Terms of the Use of Photovoltaics before and during the COVID-19 Pandemic. *Energies* **2022**, *15*, 188. [CrossRef]

7. Dzikuć, M.; Piwowar, A.; Dzikuć, M. The importance and potential of photovoltaics in the context of low-carbon development in Poland. *Energy Storage Sav.* **2022**, *1*, 162–165. [CrossRef]
8. Kulpa, J.; Olczak, P.; Stecuła, K.; Sołtysik, M. The Impact of RES Development in Poland on the Change of the Energy Generation Profile and Reduction of CO_2 Emissions. *Appl. Sci.* **2022**, *12*, 11064. [CrossRef]
9. Zdonek, I.; Tokarski, S.; Mularczyk, A.; Turek, M. Evaluation of the Program Subsidizing Prosumer Photovoltaic Sources in Poland. *Energies* **2022**, *15*, 846. [CrossRef]
10. Szablicki, M.; Rzepka, P.; Soltysik, M.; Czapaj, R. The idea of non-restricted use of LV networks by electricity consumers, producers, and prosumers. *E3S Web Conf.* **2019**, *84*, 2014. [CrossRef]
11. Jasiński, J.; Kozakiewicz, M.; Sołtysik, M. Determinants of Energy Cooperatives' Development in Rural Areas—Evidence from Poland. *Energies* **2021**, *14*, 319. [CrossRef]
12. Stecuła, K.; Tutak, M. Causes and effects of low-stack emission in selected regions of Poland. In Proceedings of the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, Sofia, Bulgaria, 30 June–9 July 2018; Volume 18, pp. 357–364.
13. Palka, D.; Stecuła, K. Concept of technology assessment in coal mining. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *261*, 012038. [CrossRef]
14. Zołądek, M.; Filipowicz, M.; Sornek, K.; Figaj, R.D. Energy performance of the photovoltaic system in urban area—Case study. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Krakow, Poland, 14–17 November 2019; p. 012123.
15. Stecuła, K.; Olczak, P.; Kamiński, P.; Matuszewska, D.; Duong Duc, H. Towards Sustainable Transport: Techno-Economic Analysis of Investing in Hydrogen Buses in Public Transport in the Selected City of Poland. *Energies* **2022**, *15*, 9456. [CrossRef]
16. Benalcazar, P.; Komorowska, A. Prospects of green hydrogen in Poland: A techno-economic analysis using a Monte Carlo approach. *Int. J. Hydrogen Energy* **2021**, *47*, 5779–5796. [CrossRef]
17. Komorowska, A.; Benalcazar, P.; Kamiński, J. Evaluating the competitiveness and uncertainty of offshore wind-to-hydrogen production: A case study of Poland. *Int. J. Hydrogen Energy* **2023**, *48*, 14577–14590. [CrossRef]
18. Kopacz, M.; Kwaśniewski, K.; Grzesiak, P.; Kapłan, R.; Kryzia, D. Economic assessments of hydrogen production by coal gasification. *Przem. Chem.* **2016**, *95*, 241–249. [CrossRef]
19. Knutel, B.; Pierzyńska, A.; Dębowski, M.; Bukowski, P.; Dyjakon, A. Assessment of energy storage from photovoltaic installations in poland using batteries or hydrogen. *Energies* **2020**, *13*, 4023. [CrossRef]
20. Kulpa, J.; Kamiński, P.; Stecuła, K.; Prostański, D.; Matusiak, P.; Kowol, D.; Kopacz, M.; Olczak, P. Technical and Economic Aspects of Electric Energy Storage in a Mine Shaft—Budryk Case Study. *Energies* **2021**, *14*, 7337. [CrossRef]
21. Dyczko, A.; Kamiński, P.; Stecuła, K.; Prostański, D.; Kopacz, M.; Kowol, D. Thermal and mechanical energy storage as a chance for energy transformation in Poland. *Polityka Energ. Energy Policy J.* **2021**, *24*, 43–60. [CrossRef]
22. PSE Praca KSE—Generacja Źródeł Wiatrowych i Fotowoltaicznych. Doba Handlowa: 25 July 2022. Available online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/generacja-zrodel-wiatrowych (accessed on 25 June 2023).
23. PSE Dane Systemowe. Available online: https://www.pse.pl/dane-systemowe (accessed on 18 July 2023).
24. Piwowar, A.; Dzikuć, M.; Dzikuć, M. The potential of wind energy development in Poland in the context of legal and economic changes. *Acta Polytech. Hungarica* 2023, *in press*.
25. Komorowska, A.; Gawlik, L. Management of surplus electricity production from unstable renewable energy sources using Power to Gas technology. *Polityka Energ. Energy Policy J.* **2018**, *21*, 43–64. [CrossRef]
26. Ceran, B.; Jurasz, J.; Mielcarek, A.; Campana, P.E. PV systems integrated with commercial buildings for local and national peak load shaving in Poland. *J. Clean. Prod.* **2021**, *322*, 129076. [CrossRef]
27. Hou, Q.; Zhang, N.; Du, E.; Miao, M.; Peng, F.; Kang, C. Probabilistic duck curve in high PV penetration power system: Concept, modeling, and empirical analysis in China. *Appl. Energy* **2019**, *242*, 205–215. [CrossRef]
28. Olczak, P.; Jaśko, P.; Kryzia, D.; Matuszewska, D.; Fyk, M.I.; Dyczko, A. Analyses of duck curve phenomena potential in polish PV prosumer households' installations. *Energy Rep.* **2021**, *7*, 4609–4622. [CrossRef]
29. Sołtysik, M.; Mucha-Kuś, K.; Kamiński, J. The New Model of Energy Cluster Management and Functioning. *Energies* **2022**, *15*, 6748. [CrossRef]
30. Borodina, O.; Bratus, H.; Udovychenko, V.; Kaczmarzewski, S.; Kostrychenko, V.; Koval, V. Renovation management of the national economy in ensuring energy decentralization. *Polityka Energ. Energy Policy J.* **2022**, *25*, 67–84. [CrossRef]
31. Kaszyński, P.; Komorowska, A.; Zamasz, K.; Kinelski, G.; Kamiński, J. Capacity Market and (the Lack of) New Investments: Evidence from Poland. *Energies* **2021**, *14*, 7843. [CrossRef]
32. Koval, V.; Sribna, Y.; Kaczmarzewski, S.; Shapovalova, A.; Stupnytskyi, V. Regulatory policy of renewable energy sources in the European national economies. *Polityka Energ. Energy Policy J.* **2021**, *24*, 61–78. [CrossRef]
33. Mreńca, E. *Energetyka Jądrowa a Ochrona Klimatu Wybrane Zagadnienia*; Gawłowski, S., Ed.; Wydawnictwo Senackie: Warsaw, Poland, 2023.
34. Simões, M.G.; Farret, F.A.; Khajeh, H.; Shahparasti, M.; Laaksonen, H. Future Renewable Energy Communities Based Flexible Power Systems. *Appl. Sci.* **2022**, *12*, 121. [CrossRef]
35. Basit, A.; Ahmad, T.; Yar Ali, A.; Ullah, K.; Mufti, G.; Hansen, A.D. Flexible Modern Power System: Real-Time Power Balancing through Load and Wind Power. *Energies* **2019**, *12*, 1710. [CrossRef]

36. Brauers, H.; Oei, P.Y. The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels. *Energy Policy* **2020**, *144*, 111621. [CrossRef]
37. Sobczyk, W.; Sobczyk, E.J. Varying the Energy Mix in the EU-28 and in Poland as a Step towards Sustainable Development. *Energies* **2021**, *14*, 1502. [CrossRef]
38. PSE. Praca KSE-Generacja mocy Jednostek Wytwórczych. Available online: https://www.pse.pl/pl_PL/dane-systemowe/funkcjonowanie-kse/raporty-dobowe-z-pracy-kse/generacja-mocy-jednostek-wytworczych (accessed on 25 June 2023).
39. Kryzia, D.; Kopacz, M.; Kryzia, K. The Valuation of the Operational Flexibility of the Energy Investment Project Based on a Gas-Fired Power Plant. *Energies* **2020**, *13*, 1567. [CrossRef]
40. Komorowska, A.; Benalcazar, P.; Kaszyński, P.; Kamiński, J. Economic consequences of a capacity market implementation: The case of Poland. *Energy Policy* **2020**, *144*, 111683. [CrossRef]
41. Komorowska, A.; Kamiński, J. A review of the 2018 Polish capacity market auctions. *Energy Policy J.* **2019**, *22*, 75–88. [CrossRef]
42. Olczak, P.; Surma, T. Energy Productivity Potential of Offshore Wind in Poland and Cooperation with Onshore Wind Farm. *Appl. Sci.* **2023**, *13*, 4258. [CrossRef]
43. Dobrzycki, A.; Roman, J. Correlation between the Production of Electricity by Offshore Wind Farms and the Demand for Electricity in Polish Conditions. *Energies* **2022**, *15*, 3669. [CrossRef]
44. Li, X.; Wang, L.; Yan, N.; Ma, R. Cooperative Dispatch of Distributed Energy Storage in Distribution Network with PV Generation Systems. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 0604304. [CrossRef]
45. Giannelos, S.; Djapic, P.; Pudjianto, D.; Strbac, G. Quantification of the Energy Storage Contribution to Security of Supply through the F-Factor Methodology. *Energies* **2020**, *13*, 826. [CrossRef]
46. Giannelos, S.; Jain, A.; Borozan, S.; Falugi, P.; Moreira, A.; Bhakar, R.; Mathur, J.; Strbac, G. Long-Term Expansion Planning of the Transmission Network in India under Multi-Dimensional Uncertainty. *Energies* **2021**, *14*, 7813. [CrossRef]
47. Kermani, M.; Shirdare, E.; Parise, G.; Bongiorno, M.; Martirano, L. A Comprehensive Technoeconomic Solution for Demand Control in Ports: Energy Storage Systems Integration. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1592–1601. [CrossRef]
48. Bozsik, N.; Szeberényi, A.; Bozsik, N. Examination of the Hungarian Electricity Industry Structure with Special Regard to Renewables. *Energies* **2023**, *16*, 3826. [CrossRef]
49. Rokicki, T.; Jadczak, R.; Kucharski, A.; Bórawski, P.; Bełdycka-Bórawska, A.; Szeberényi, A.; Perkowska, A. Changes in Energy Consumption and Energy Intensity in EU Countries as a Result of the COVID-19 Pandemic by Sector and Area Economy. *Energies* **2022**, *15*, 6243. [CrossRef]
50. Rokicki, T.; Koszela, G.; Ochnio, L.; Perkowska, A.; Bórawski, P.; Bełdycka-Bórawska, A.; Gradziuk, B.; Gradziuk, P.; Agnieszka, S.; Szeberényi, A.; et al. Changes in the production of energy from renewable sources in the countries of Central and Eastern Europe. *Front. Energy Res.* **2022**, *10*, 993547. [CrossRef]
51. Environment, M. of C. and Polityka energetyczna Polski do 2040 r. Available online: https://www.gov.pl/web/klimat/minister-kurtyka-polityka-energetyczna-polski-do-2040-r-udziela-odpowiedzi-na-najwazniejsze-wyzwania-stojace-przed-polska-energetyka-w-najblizszych-dziesiecioleciach (accessed on 21 January 2021).