POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2025 ✦ Volume 28 ✦ Issue 2 ✦ 5–22

DOI: 10.33223/epj/202557

Marcel Kościelny[1], Piotr Olczak[2]

Comparative LCOE/LCA and maintenance/service analysis of renewable energy sources in the context of curtailment with the regional diversity in Poland

Abstract: In recent years, the increase in the share of unstable energy sources classified as renewable energy sources, wind turbines, and photovoltaic installations in the national (Polish) energy mix has led to the emergence of new challenges. These challenges include what to do with excess energy production in the face of low prices and low storage capacities. The solution used in 2023 and 2024 was the forced shutdown of sources on the scale of the national power system. A gap was noticed in the methodology for assessing which installations (wind turbines or photovoltaics) should be shut down on the scale of one power connection in the so-called cable pooling cooperation formula. In this respect, a decision-making methodology was developed for shutting down generating capacity based on operating costs. Scenarios for the installed capacity of individual sources were defined: photovoltaic installations and wind turbines. Then, an analysis of scenarios of different capacities of individual farms was performed compared to one side of the power connection. It was proven that in most cases of cooperation between photovoltaic farms and wind farms, wind farms should be shut down first in the event of exceeding the capacity from the point of view of one owner for one connection for these farms. The results also voiced the discussion on compensation for installation

✉ Corresponding Author: Piotr Olczak; e-mail: olczak@min-pan.krakow.pl

[1] AGH University of Science and Technology, Kraków, Poland; e-mail: mkoscielny@student.agh.edu.pl

[2] The Department of Minerals and Energy Market Research, Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Poland; ORCID iD: 0000-0002-4926-0845; e-mail: olczak@min-pan.krakow.pl

shutdowns on the scale of the entire power system in Poland. Nevertheless, the estimates in this area have a wide area for in-depth analyses for individual sources, taking into account various conditions, e.g., age of devices, local conditions.

Keywords: photovoltaic, wind turbine, maintenance cost, LCOE, cable pooling

Introduction

Poland and Europe have been going through reforms during the last decade in the energy production field. The high level of development in renewable energy production in Poland (32.6% increase in the years 2012–2022 via the Eurostat) was caused by plans of the European Union to reduce greenhouse gas emissions (REPowerEU, Fit for 55; Dzikuć et al. 2021; Piwowar and Dzikuć 2019; Sornek 2024) and increase the energy security and (Paska and Surma 2016). The growth of renewable energy comes with an increased amount of renewable energy power plants. According to the Energy Regulatory Office, in 2023, the number of renewable energy power plants in Poland was 7004 (Urząd Regulacji Energetyki 2024). Taking into consideration the method of operation of renewable energy production (solar power being dependent on sun exposure (Sadowska et al. 2024; Sawicka-Chudy et al. 2018); wind power being dependent on wind speed) (Stecuła and Brodny 2017; Stecuła and Tutak 2018), the energy production is dependent on atmospheric factors, which change daily (Canales et al. 2020; Ciapała et al. 2021; Jurasz and Ciapała 2019). Combined with other factors that have an impact on energy production, like decreased energy demand, controlled curtailment of renewable energy sources can be beneficial. The effect of increasing the share of energy from photovoltaics on indicators related to broadly understood sustainable development was analyzed by (Sribna et al. 2021), as well as the impact on energy security (Hrinchenko et al. 2023; Skoczkowski et al. 2016, 2024). On the other hand, the technical and economic aspects of increasing the amount of installed power in power systems through solar devices were analyzed (Chwieduk et al. 2020; Koval et al. 2024).

The influence of various parameters, such as solar irradiance, weather conditions, and humidity on Photovoltaic energy production was analyzed (Shaik et al. 2023) and for Poland (Olczak 2022; Zarębska and Dzikuć 2013). Studies about wind turbine energy generation for different regions and periods in Poland have also been made, as well as SWOT analysis (Igliński et al. 2016). LCA analysis of solar farms with the CED method has been conducted (Leda et al. 2023; Żelazna and Gołębiowska 2015). For wind energy, an LCA analysis shows its impact on the environment of all relevant inputs through its production, raw materials, and transportation (Bracquene et al. 2018; Turkmen and Babuna 2024). General curtailment analysis of PV and wind turbines has been made (Gagrica et al. 2016; Luthander et al. 2016), but only for the country of Canada (O'Shaughnessy et al. 2020).

LCOE analysis for building integrated photovoltaic systems (BIPV) was made for the general European market (Gholami and Røstvik 2021). LCOE analysis (Nieto-Diaz 2022), CAPEX, and OPEX were made for wind turbines operating off-shore (Ioannou et al. 2018). There haven't been enough studies made in the context of Polish regional diversity in terms of which and when renewable energy sources should be curtailed (when it is needed). Different analysis shows how curtailment can be caused by different drivers, such as geographic mismatch between solar resource and load/transmission expansion, Grid congestion, systemwide oversupply, as well as oversupply in regional markets (O'Shaughnessy et al. 2020). This study aims to conduct a comparative LCOE/LCA and maintenance/service analysis of renewable energy sources in the context of curtailment with the regional diversity in Poland.

The first chapter contains the analysis (methods), and the second chapter contains results and the last one conclusions.

1. Methods

The analysis was made for both wind and solar power installations. Wind turbines show a yearly degradation rate of –0.52%, which means that in a 20-year time, there will be a 10% efficiency loss for an average wind turbine during its exploitation (Kim et al. 2021). For aerodynamic rotating machines, which include wind turbines, a significant part of irreversible losses can be attributed to mechanical degradation of its parts, such as bearings and turbine blades (Staffell and Green 2014). Material fatigue is often caused by constant workload that, in turn, can crack the surface of the bearing. If external forces work on a bearing's rings, its material will lose durability and start cracking. In time, the cracking continues, and eventually, the bearing will be unfit for exploitation (Kudelina et al. 2022). On the other hand, high workloads on turbine blades, which often are made from glass-fiber-reinforced or carbon-fiber-reinforced polymers, cause damage such as transverse cracks (Wang et al. 2022). To continue the turbine's operation, the damaged element needs to be replaced, which in turn increases the lifetime environmental impact of the turbine. Based on the analysis of over 2000 PV panels, it's been proven that their average yearly degradation rate is about –0.8%, which is higher than the wind turbine degradation rate (Jordan and Kurtz 2013). Working under high temperatures is a significant reason for the degradation of PV panels. Work under high temperatures causes damages that come from thermal stress inside the panel or from electrical resistance during energy production (Rahman et al. 2023). Also, working under low humidity increases the probability of damaging the encapsulant, making it so that yellowing appears on the surface of the panel, lowering its efficiency (Mahdi et al. 2024). Taking it all into consideration, we can say that there are multiple factors impacting the aging of renewable energy sources. These factors impact the decision to curtail. Another factor to consider is how feasible it is to shut down a power source. Wind turbines work by putting the turbine blades in a neutral position so that the wind does not have any effect on the turbine's movement. This method is convenient and cost-efficient. For PV panels, turning off becomes much more difficult. The first method is covering up solar panels. This method would require a huge financial investment due to the significant size of solar farms. The other method is using a tracking system for solar panels to steer the panel away from the sun. This method, just like the previous one, requires a huge financial investment if the system is not already in place (Ma et al. 2011; Zhang et al. 2018). Taking that into consideration, turning off wind turbines is much more feasible due to their ease of operation. Another crucial factor is weather conditions. Due to their design, most wind turbines work within the wind speed limit of 5–25 m/s. Although solar panels don't have that restriction, they, on average, work best at panel temperature of 25 degrees Celsius. Taking that all into consideration, the most favorable conditions for curtailment of renewable sources would be a day with a wind speed of about 25 m/s (Piwowar et al. 2023), high humidity, and moderate temperature so that wind turbines can be shut off at low cost and the PV panels can work at the most favorable conditions. LCOE is defined as a ratio of the sum of capital investment and operation costs and electricity produced over its lifetime (Nieto-Diaz 2022; Vartiainen et al. 2020). Investment costs are not taken into consideration in this analysis because they do not impact the decision to turn off renewable sources. As renewable energy sources get shut off, they do not produce any energy. Therefore, LCOE is higher, but considering the reduction of potential damage and loss of efficiency, it can actually decrease. Unfortunately, this only applies to wind turbines, as shutting off PV panels would cause operational costs to skyrocket, resulting in much higher LCOE. When integrating renewable sources into energy systems, hybrid systems that complement each other, such as wind-solar coupling and wind-solar-hydro coupling, can be connected by cable pooling, which enables better optimization and operation. Despite the advantages of cable pooling, there are some problems. One of them is excess electricity production, which has to be resolved by reducing the production of selected sources or by connecting an energy magazine. Unfortunately, energy magazines are rare in Poland, so energy production has to be reduced a lot of the time. Energy source production reductions are managed by "Polish Power Grids", which for example, in 2022, ordered a 400–800 MWh wind energy production reduction; in 2023, total reduced energy production was higher than in 2022. In solar energy, there have been problems with companies not acquiring financial compensation for production reductions. Unclear compensation acquisition procedures cause that problem. To properly analyze cable pooling, a simulation of both wind and solar energy generation in a cable-pooled configuration will be analyzed. The statistics for analysis were taken from 2022 and 2023 and focused on off-shore wind turbines and PV panels. Only two years were taken into account, as more is not needed to draw appropriate conclusions.

1.1. Formulas

The analysis will begin by defining each analyzed element.

- Average yearly installed RES power, which is defined as:

$$Pa(so, year) = \frac{Pz1(so, year) + Pz2(so, year)}{2} \tag{1}$$

where:

Pa	–	average yearly RES installed power [MW],
so	–	analyzed renewable energy source which is PV or wind turbine (wt),
$year$	–	year of the analyzed example,
$Pz1$	–	installed RES power during the first day of the year [MW],
$Pz2$	–	installed RES power during the last day of the year [MW].

- Renewable energy source factor, which is defined as:

$$RESf(so, hy, year) = \frac{E(so, hy, year)}{Pa(so, year)} \tag{2}$$

where:

$RESf$	–	renewable energy source factor, defined as hourly energy production value working with source's maximum power [h],
E	–	hourly renewable energy production from source so [MWh],
so	–	analyzed renewable energy source which is PV or wind turbine,
Pa	–	average yearly RES installed power [MW],
$year$	–	year of a analyzed example,
hy	–	hour of the year.

- Simulated renewable energy production of a analyzed power, which is defined as:

$$RESp(so, hy, year) = RESf(so, hy, year) \cdot Pc(so, year) \tag{3}$$

where:

$RESp$	–	simulated renewable energy source production of a analyzed power [MWh],
so	–	analyzed renewable energy source which is PV or wind turbine (wt),
$RESf$	–	renewable energy source factor, defined as hourly energy production value working with source's maximum power [h],
hy	–	hour of the year,
$year$	–	year of an analyzed example,
Pc	–	simulated power of an installed source, assumed as 8, 10, 12, 14, 16 [MW].

✦ Overproduction energy value, which is defined as:

$$Eovp(hy, year) = \begin{cases} (Resp(wt, hy, year) + RESp(PV, hy, year)) - Pmax, \\ if\, (RESp(wt, hy, year) + RESp(PV, hy, year)) > Pmax; \\ 0,\; if\, (RESp(wt, hy, year) + RESp(PV, hy, year)) < Pmax \end{cases} \tag{4}$$

where:

Eovp – overproduction energy value [MWh],
RESp – simulated renewable energy source production of a analyzed power [MWh],
Pmax – maximum amount of energy that can be sent through cable pooling restrictions [MWh],
so – analyzed renewable energy source which is PV or wind turbine,
hy – hour of the year,
year – year of a analyzed example.

1.2. Calculations

The next step will be to calculate the average renewable energy power installed in a given year. This is done in order to simplify the process of calculating other elements of the analysis, as it would be inefficient to calculate hourly power installed changes. The calculation is done for the years 2022 and 2023. For 2022, wind turbines installed power on 01.01.2022 was 7,224.97 MW; for 31.12.2022, it was 8,287.87 MW, giving the average value of (Pa(WT,2022)) 7,756.42 MW. For PV, the average value was (Pa(PV, 2022)) 10,050 MW. In 2023 average wind turbines installed power was (Pa(wt,2023)) 8,393,94 MW and for PV it was (Pa(PV, 2023))14,740 MW based on values from the renewable energy regulatory office (Moc Zainstalowana (MW) – Potencjał Krajowy OZE w Liczbach – Urząd Regulacji Energetyki 2024) and Renewable Energy Institute statistics (Report „Photovoltaic Market in Poland 2023" – EC BREC Institute of Renewable Energy/Photovoltaics 2024)

In the next step *RESf* will be calculated for hourly RES production, for example on 3/28/2022 wind turbines energy production was 4,647 MWh, PV energy production was 4,695 MWh. Using the formula for *RESf*:

Wind turbines: *RESf* = (4,647/7,756.42) = 0.599

PV: *RESf* = (4,695/10,050) = 0.467

Hourly values for both 2022 and 2023 have been calculated. The next step will be to calculate the simulated RES production, which will be calculated for each source, year, and hour using the formula written previously in the analysis. After that, values of PV and wind turbine *RESp* will be summed for each hour. Then, the overproduction of energy, which was defined previously in the analysis, will be calculated. *Pmax* value, which is the maximum amount of energy that can be sent through cable pooling restrictions, will be assumed to be 10 MW for the remainder of the analysis. Overproduction value will be calculated for four different *Pc* values, which are chosen as 8, 10, 12, 14 and 16 MW for both PV and wind turbines.

2. Results

Values of *RESf* have been sorted from highest to lowest for each year and source and arranged in a graph. Results are presented below.

Based on the results, *RESf* values higher than 0.2 will be found, as well as the percentage of the year with these values present. In 2022, the percentage of the year with *RESf* exceeding 0.2 was 52.39% for wind turbines and 22.87% for PV panels. In 2023, the percentage of the year with *RESf* values exceeding 0.2 was 54.57% for wind turbines and 21.64% for PV panels.

Further analysis reveals that graphs for daily energy overproduction for 2022 and 2023 are shown below. The PC value selected for both graphs was 16 MW.

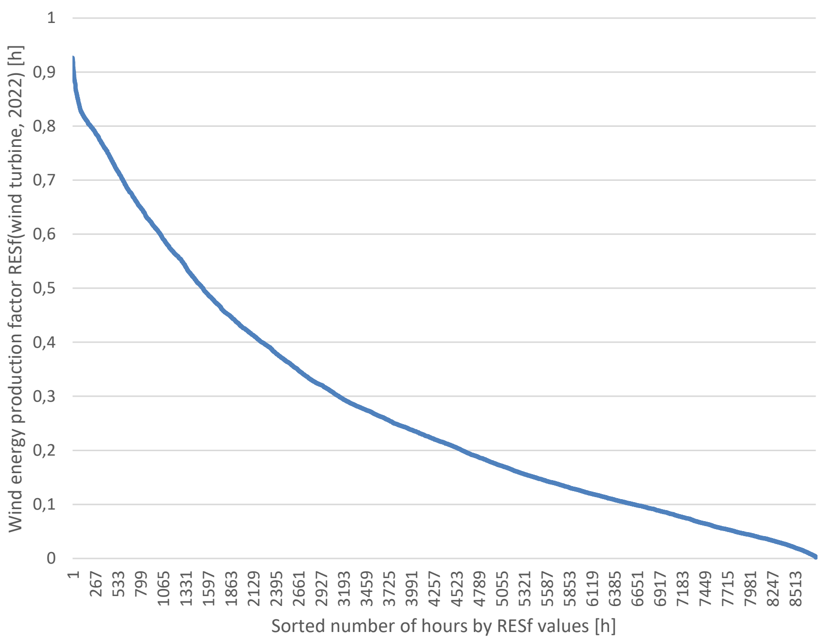

Fig. 1. Wind energy production factor graph for the year 2022

Rys. 1. Wykres współczynnika produkcji energii wiatrowej na rok 2022

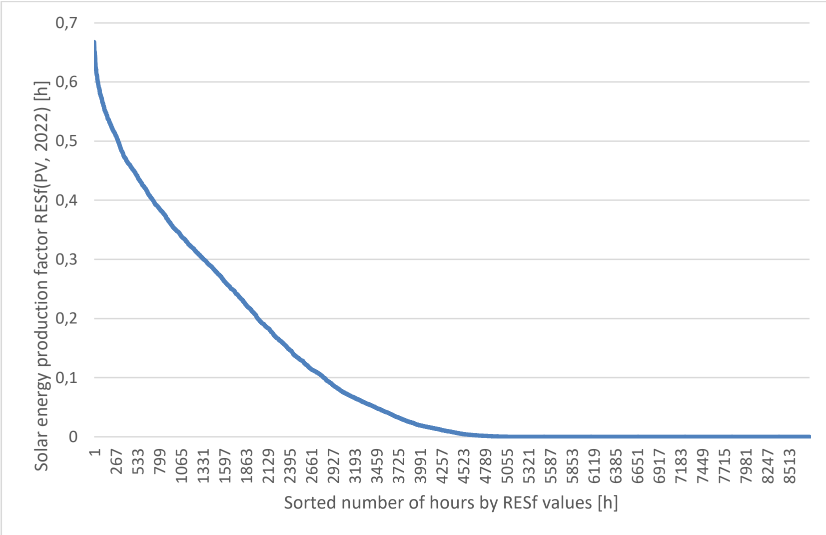

Fig. 2. Solar energy production factor graph for the year 2022

Rys. 2. Wykres współczynnika produkcji energii słonecznej na rok 2022

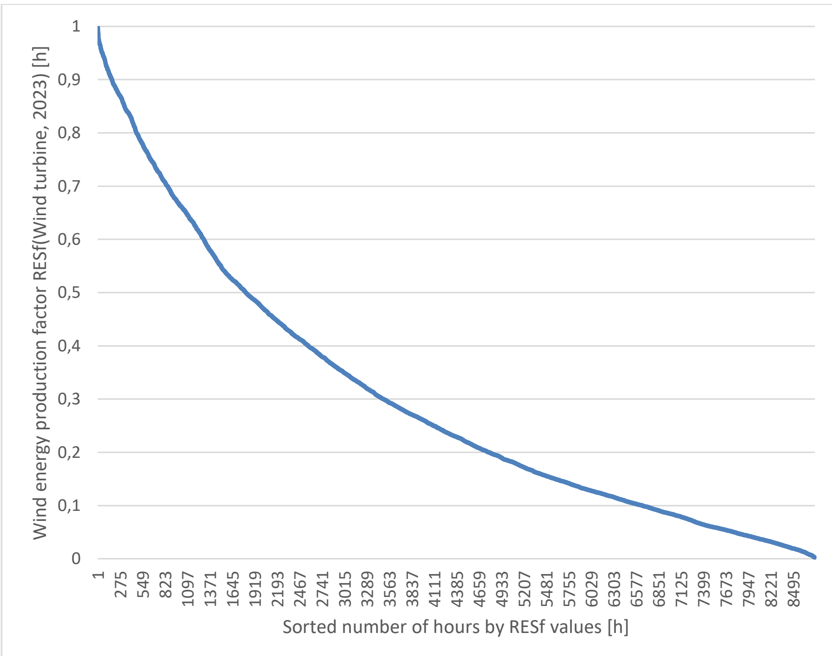

Fig. 3. Wind energy production factor graph for the year 2023

Rys. 3. Wykres współczynnika produkcji energii wiatrowej na rok 2023

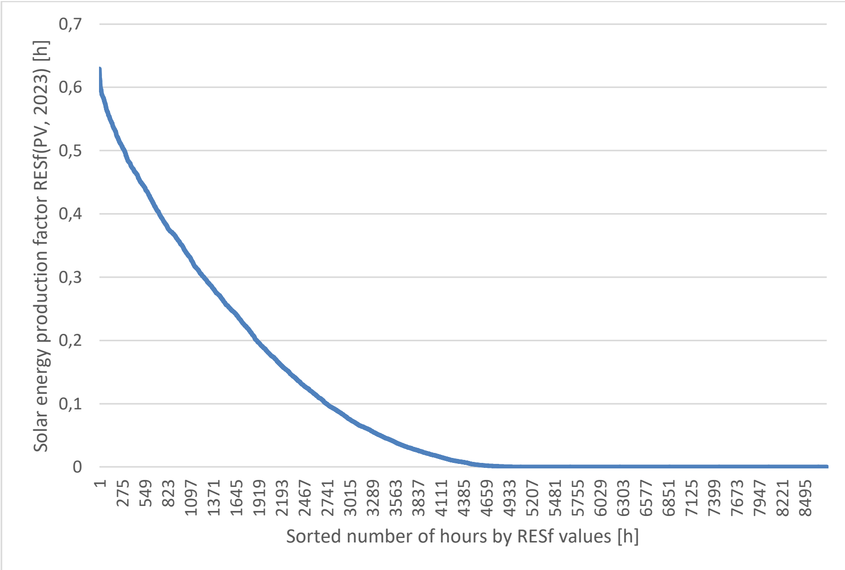

Fig. 4. Solar energy production factor graph for the year 2023

Rys. 4. Wykres współczynnika produkcji energii słonecznej na rok 2023

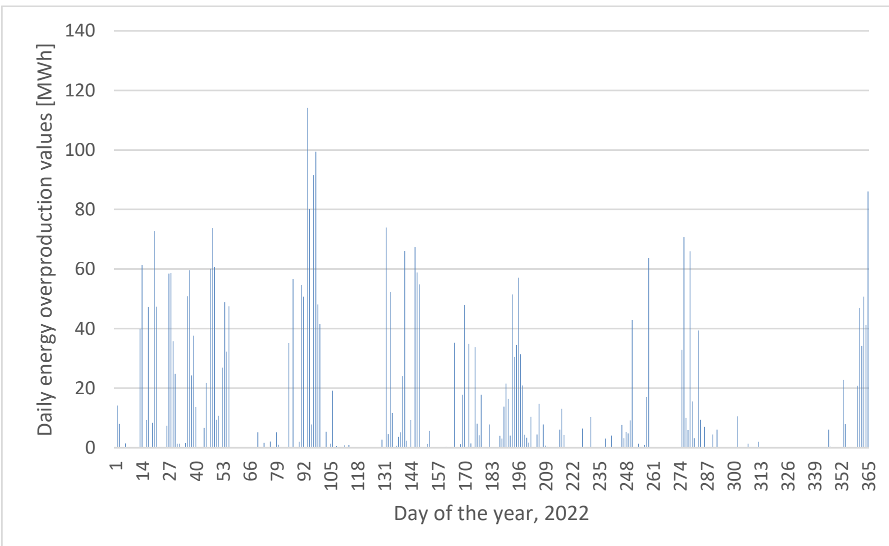

Fig. 5. Daily energy overproduction graph for the year 2022 for *Pc* value of 16 MW

Rys. 5. Wykres dobowej nadprodukcji energii dla roku 2022 dla wartości *Pc* 16 MW

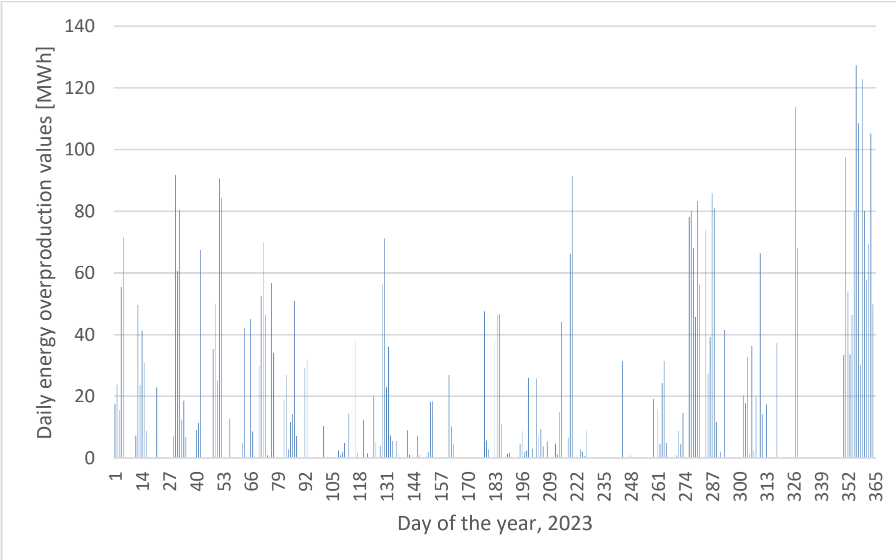

Fig. 6. Daily energy overproduction graph for the year 2023 for *Pc* value of 16 MW

Rys. 6. Wykres dobowej nadprodukcji energii dla roku 2023 dla wartości *Pc* 16 MW

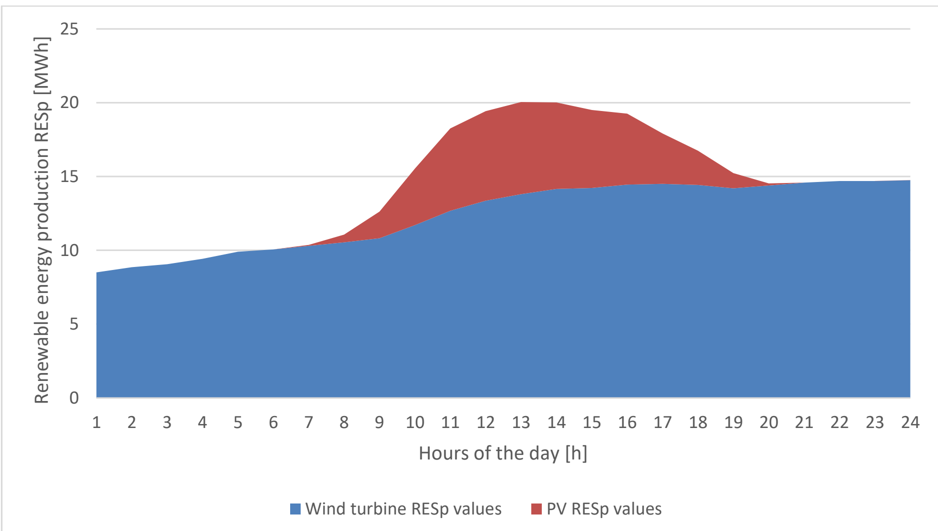

Fig. 7. *RESp* values graph for the highest production day for wind turbines and PV in 2022 for *Pc* values of 16 MW

Rys. 7. Wykres wartości *RESp* dla dnia największej produkcji turbin wiatrowych i fotowoltaicznych w 2022 r. dla wartości *Pc* wynoszących 16 MW

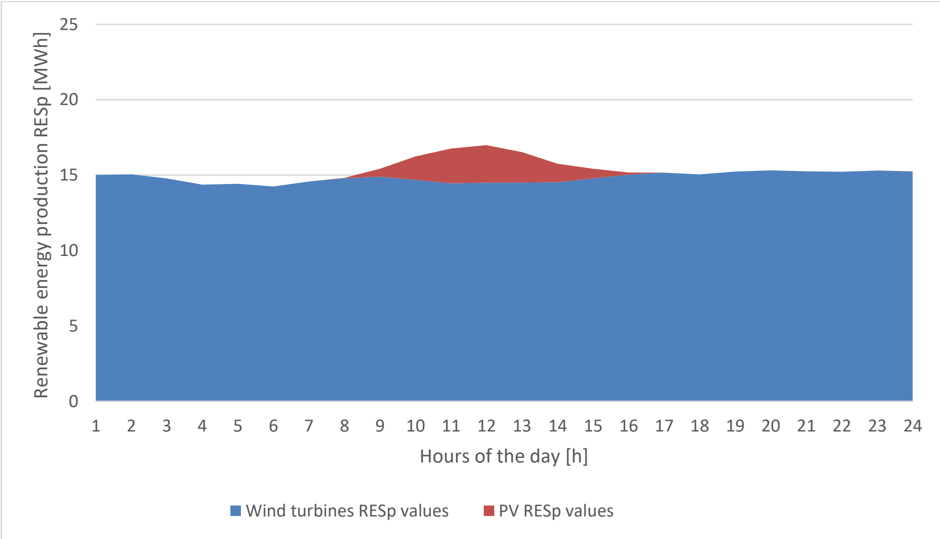

Fig. 8. *RESp* values graph for the highest production day for wind turbines and PV in 2023 for *Pc* values of 16 MW

Rys. 8. Wykres wartości *RESp* dla dnia największej produkcji turbin wiatrowych i PV w 2023 r. dla wartości *Pc* wynoszących 16 MW

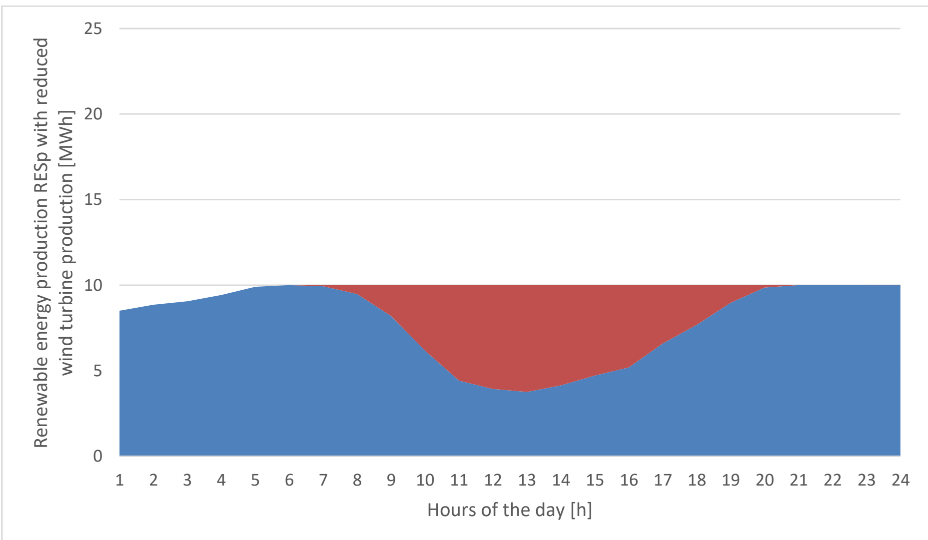

Fig. 9. *RESp* graph for wind turbines and PV with reduced wind turbine energy production for 04/4/2022

Rys. 9. Wykres *RESp* dla turbin wiatrowych i PV przy zmniejszonej produkcji energii z turbin wiatrowych na 04.04.2022 r.

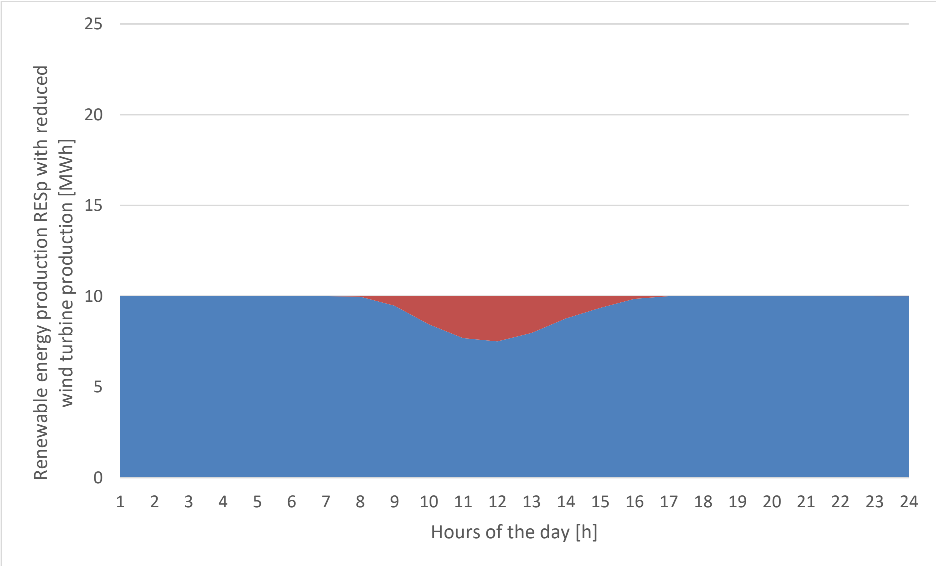

Fig. 10. *RESp* graph for wind turbines and PV with reduced wind turbine energy production for 20/12/2023

Rys. 10. Wykres *RESp* dla turbin wiatrowych i PV przy obniżonej produkcji energii z turbin wiatrowych na 20.12.2023 r.

As shown, the day with the highest energy overproduction in 2022 is 04/4/2022, with a value of 114.12 MWh. The day with the highest energy overproduction in 2023 is 20/12/2023, with a value of 127.35 MWh. To analyze further, graphs for days with the highest overproduction values for each year and renewable sources have been charted and presented below. The PC value for both graphs was selected as 16 MW.

As shown above, wind energy is the primary source of overproduction during the year for both 2022 and 2023. Therefore, its curtailing would be the most efficient. The exemplary curtailment of wind energy is presented below for previously shown days.

The overall wind turbine energy production loss for 04/4/2022 was 36.7%, and for 20/12/2023, it was 35.8%. The reduction in 2022 was higher due to increased peak energy production, which required a bigger reduction.

Overproduction values for each year based on *Pc* values presented in calculations have been charted on a graph:

As presented above, the overproduction rate for increasing RES power increases non-linearly. That is caused by increased losses per hour combined with more hours where the overproduction occurs. In 2023 the Eovp values were much higher than 2022's values, which means that the energy production loss was greater. To analyze the data further calculation for overall yearly lost energy for 16 MW energy source power will be made by dividing the overall energy produced with overproduced energy. In 2022 the yearly loss of energy came out to 6.91% and in 2023 8.96%, calculated as ratio of the yearly overproduced energy to total yearly produced energy

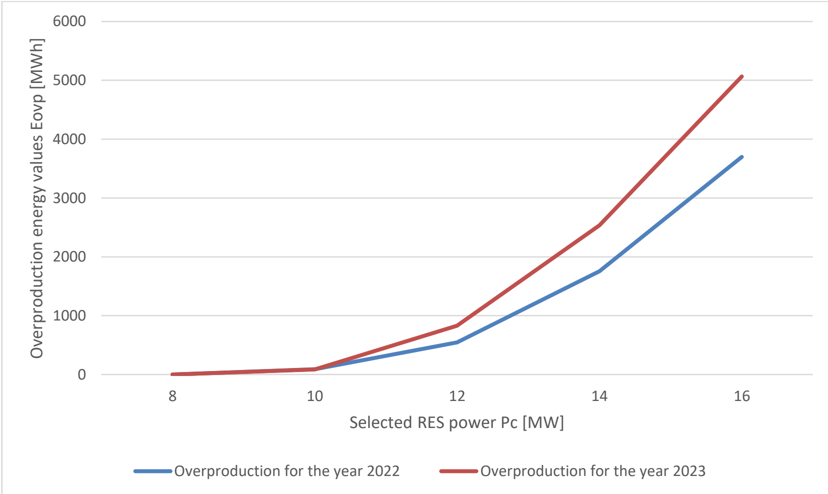

Fig. 11. RES overproduction energy graph for selected installation powers (PV and wind turbines the same power *Pc*) in case when *Pmax* is 10 MWh in 2022 and 2023

Rys. 11. Wykres nadprodukcji energii z OZE dla wybranych mocy instalacji (turbiny fotowoltaiczne i wiatrowe o tej samej mocy *Pc*) w przypadku, gdy *Pmax* wynosi 10 MWh w latach 2022 i 2023

by PV and wind turbines. Wind production loss after reduction shown in Figure 7 and 8, which is calculated as ratio of the reduced production sum to yearly production sum of wind turbines, equals to 0.28% in the year 2022 and 0.30% in 2023.

Conclusions

With the increase of renewable source development in Poland, driven by EU policies that focus on reducing greenhouse emissions and increasing energy security, more and more energy sources need to reduce their energy production. Due to the lack of suitable curtailment methods for PV panels, wind turbines are better options for reducing energy production; their highest energy production loss was 36.7% of total production in 04/4/2022 and 35.8% in 20/12/2023. With the continued development of renewable energy technologies and the Polish government's inclination to support them, the overproduction of energy from renewable sources will continue to rise from year to year. Due to decreased work-loads, wind turbine elements such as turbine blades and bearings sustain reduced mechanical damage, which reduces the need for replacement, reducing the overall environmental impact of renewable sources and increasing their efficiency and life span. Wide-spread adoption of cable-pooling technology in renewable source installations can help with curtailment as PV panel and wind turbine energy generation complement each other during the day, meaning that installations don't need to reduce energy production as much as they would have if they were being connected separately, increasing their cost-effectiveness. Curtailments of renewable energy sources can have a significant impact on energy production. As this study mainly focuses on offshore wind turbines, future studies can include a more detailed analysis of the regional impact on curtailment strategy.

The Authors have no conflicts of interest to declare.

References

Bracquene et al. 2018 – Bracquene, E., Peeters, J.R., Dewulf, W. and Duflou, J.R. 2018. Taking Evolution into Account in a Parametric LCA Model for PV Panels. *Procedia CIRP* 69, pp. 389–394, DOI: 10.1016/J.PROCIR.2017.11.103.

Canales et al. 2020 – Canales, F.A., Jadwiszczak, P., Jurasz, J., Wdowikowski, M., Ciapała, B. and Kaźmierczak, B. 2020. The impact of long-term changes in air temperature on renewable energy in Poland. *Science of the Total Environment* 729, DOI: 10.1016/j.scitotenv.2020.138965.

Chwieduk et al. 2020 – Chwieduk, D., Bujalski, W. and Chwieduk, B. 2020. Possibilities of transition from centralized energy systems to distributed energy sources in large polish cities. *Energies* 13(22), DOI: 10.3390/en13226007.

Ciapała et al. 2021 – Ciapała, B., Jurasz, J., Janowski, M. and Kępińska, B. 2021. Climate factors influencing effective use of geothermal resources in SE Poland: the Lublin trough. *Geothermal Energy* 9(1), DOI: 10.1186/s40517-021-00184-1.

Dzikuć et al. 2021 – Dzikuć, M., Gorączkowska, J., Piwowar, A., Dzikuć, M., Smoleński, R. and Kułyk, P. 2021. The analysis of the innovative potential of the energy sector and low-carbon development: A case study for Poland. *Energy Strategy Reviews* 38, DOI: 10.1016/j.esr.2021.100769.

Gagrica et al. 2016 – Gagrica, O., Marzec, M. and Uhl, T. 2016. Comparison of reliability impacts of two active power curtailment methods for PV micro-inverters. *Microelectronics Reliability* 58, pp. 133–140, DOI: 10.1016/j.microrel.2015.11.031.

Gholami, H. and Røstvik, H.N. 2021. Levelised cost of electricity (LCOE) of building integrated photovoltaics (BIPV) in Europe, rational feed-in tariffs and subsidies. *Energies* 14(9), DOI: 10.3390/EN14092531/S1.

Hrinchenko et al. 2023 – Hrinchenko, H., Koval, V., Shmygol, N., Sydorov, O., Tsimoshynska, O. and Matuszewska, D. 2023. Approaches to Sustainable Energy Management in Ensuring Safety of Power Equipment Operation. *Energies* 16(18), DOI: 10.3390/en16186488.

Igliński et al. 2016 – Igliński, B., Iglińska, A., Koziński, G., Skrzatek, M. and Buczkowski, R. 2016. Wind energy in Poland – History, current state, surveys, Renewable Energy Sources Act, SWOT analysis. *Renewable and Sustainable Energy Reviews* 64, pp. 19–33, DOI: 10.1016/j.rser.2016.05.081.

Ioannou et al. 2018 – Ioannou, A., Angus, A. and Brennan, F. 2018. Parametric CAPEX, OPEX, and LCOE expressions for offshore wind farms based on global deployment parameters. *Energy Sources, Part B: Economics, Planning, and Policy* 13(5), pp. 281–290, DOI: 10.1080/15567249.2018.1461150.

Jordan, D.C. and Kurtz, S.R. 2013. Photovoltaic Degradation Rates – an Analytical Review. *Progress in Photovoltaics: Research and Applications* 21(1), pp. 12–29, DOI: 10.1002/PIP.1182.

Jurasz, J. and Ciapała, B. 2019. A solar- and wind-powered charging station for electric buses based on a backup batteries concept. *ICT for Electric Vehicle Integration with the Smart Grid*, pp. 317–335, DOI: 10.1049/pbtr016e_ch12.

Kim et al. 2021 Kim, H.-G., Kim, J.-Y., Kim, H.-G., Kim, J.-Y. and Castellani, F. 2021. Analysis of Wind Turbine Aging through Operation Data Calibrated by LiDAR Measurement. *Energies* 14(8), DOI: 10.3390/EN14082319.

Koval et al. 2024 – Koval, V., Sribna, Y., Brednyova, V., Kosharska, L., Halushchak, M. and Kopacz, M. 2024. An analysis of the economic and technological potential of solar-driven generation in renewable energy development. *Polityka Energetyczna – Energy Policy Journal* 27(1), pp. 157–172, DOI: 10.33223/epj/184181.

Kudelina et al. 2022 – Kudelina, K., Baraškova, T., Shirokova, V., Vaimann, T. and Rassõlkin, A. 2022. Fault Detecting Accuracy of Mechanical Damages in Rolling Bearings. *Machines* 10(2), DOI: 10.3390/MACHINES10020086.

Leda et al. 2023 – Leda, P., Kruszelnicka, W., Leda, A., Piasecka, I., Kłos, Z., Tomporowski, A., Flizikowski, J. and Opielak, M. 2023. Life Cycle Analysis of a Photovoltaic Power Plant Using the CED Method. *Energies* 16(24), DOI: 10.3390/EN16248098.

Luthander et al. 2016 – Luthander, R., Widén, J., Munkhammar, J. and Lingfors, D. 2016. Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment. *Energy* 112, pp. 221–231, DOI: 10.1016/j.energy.2016.06.039.

Ma et al. 2011 – Ma, Y., Li, G. and Tang, R. 2011. Optical performance of vertical axis three azimuth angles tracked solar panels. *Applied Energy* 88(5), pp. 1784–1791, DOI: 10.1016/J.APENERGY.2010.12.018.

Mahdi et al. 2024 – Mahdi, A., Leahy, H., Alghoul, P. G., Morrison, M., Al Mahdi, H., Leahy, P.G., Alghoul, M. and Morrison, A.P. 2024. A Review of Photovoltaic Module Failure and Degradation Mechanisms: Causes and Detection Techniques. *Solar* 4(1), pp. 43–82, DOI: 10.3390/SOLAR4010003.

Installed capacity (MW) – National renewable energy potential in numbers – Energy Regulatory Office (*Moc zainstalowana* (*MW*) *– Potencjał krajowy OZE w liczbach – Urząd Regulacji Energetyki*) (n.d.). [Online] https://www.ure.gov.pl/pl/oze/potencjal-krajowy-oze/5753,Moc-zainstalowana-MW.html [Accessed: 2024-06-29] (*in Polish*).

Nieto-Diaz, B.A. 2022. *Increased lifetime of Organic Photovoltaics (OPVs) and the impact of degradation, efficiency and costs in the LCOE of Emerging PVs*. Durham University.

Olczak, P. 2022. Comparison of modeled and measured photovoltaic microinstallation energy productivity. *Renewable Energy Focus* 43, pp. 246–254, DOI: 10.1016/j.ref.2022.10.003.

O'Shaughnessy et al. 2020 – O'Shaughnessy, E., Cruce, J. R. and Xu, K. 2020. Too much of a good thing? Global trends in the curtailment of solar PV. *Solar Energy* 208, pp. 1068–1077, DOI: 10.1016/J.SOLENER.2020.08.075.

Paska, J. and Surma, T. 2016. Wpływ polityki energetycznej Unii Europejskiej na funkcjonowanie przedsiębiorstw energetycznych w Polsce. *Rynek Energii* 123(2), pp. 17–26.

Piwowar, A. and Dzikuć, M. 2019. Development of Renewable Energy Sources in the Context of Threats Resulting from Low-Altitude Emissions in Rural Areas in Poland: A Review. *Energies* 12(18), DOI: 10.3390/en12183558.

Piwowar et al. 2023 – Piwowar, A., Dzikuć, M. and Dzikuć, M. 2023. The potential of wind energy development in Poland in the context of legal and economic changes. *Acta Polytechnica Hungarica* 20(10), pp. 145–156.

Rahman et al. 2023 – Rahman, T., Mansur, A. Al, Hossain Lipu, M.S., Rahman, M.S., Ashique, R.H., Houran, M.A., Elavarasan, R.M. and Hossain, E. 2023. Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management. *Energies* 16(9), DOI: 10.3390/EN16093706.

Renewable energy source installations – as of 31 December 2023 – Domestic renewable energy potential in numbers – Energy Regulatory Office (*Instalacje odnawialnych źródeł energii – stan na 31 grudnia 2023 r. – Potencjał krajowy OZE w liczbach – Urząd Regulacji Energetyki*) (n.d.). [Online] https://www.ure.gov.pl/pl/oze/potencjal-krajowy-oze/8108,Instalacje-odnawialnych-zrodel-energii-stan-na-31-grudnia-2023-r.html [Accessed: 2024-06-29] (*in Polish*).

Report „Photovoltaic Market in Poland 2023" – EC BREC Institute of Renewable Energy | Photovoltaics (*Raport „Rynek fotowoltaiki w Polsce 2023" – EC BREC Instytut Energetyki Odnawialnej | Fotowoltaika*) 2024). [Online] https://ieo.pl/aktualnosci/1645-raport-rynek-fotowoltaiki-w-polsce [Accessed: 2024-06-29] (*in Polish*).

Sadowska et al. 2024 – Sadowska, G., Cholewa, T., Nižetić, S., Papaefthimiou, S., Balaras, C. A. and Arici, M. 2024. On real energy model of photovoltaic systems: Creation and validation. *Energy Conversion and Management* 315, DOI: 10.1016/j.enconman.2024.118810.

Sawicka-Chudy et al. 2018 – Sawicka-Chudy, P., Rybak-Wilusz, E., Sibiński, M., Pawełek, R., Cholewa, M. and Kaczor, M. 2018. Analysis of possibilities and demand for energy in a public building using a tracking photovoltaic installation. *E3S Web of Conferences* 49, DOI: 10.1051/e3sconf/20184900096.

Shaik et al. 2023 – Shaik, F., Lingala, S.S. and Veeraboina, P. 2023. Effect of various parameters on the performance of solar PV power plant: a review and the experimental study. *Sustainable Energy Research* 10(1), pp. 1–23, DOI: 10.1186/S40807-023-00076-X.

Skoczkowski et al. 2016 – Skoczkowski, T., Bielecki, S. and Baran, Ł. 2016. Renewable energy sources – problems and perspectives of development in Poland (*Odnawialne źródła energii – Problemy i perspektywy rozwoju w Polsce*). *Przegląd Elektrotechniczny* 2016(3), DOI: 10.15199/48.2016.03.44 (*in Polish*).

Skoczkowski et al. 2024 – Skoczkowski, T., Bielecki, S., Wołowicz, M., Sobczak, L., Węglarz, A. and Gilewski, P. 2024. Participation in demand side response. Are individual energy users interested in this? *Renewable Energy* 232, DOI: 10.1016/j.renene.2024.121104.

Sornek, K. 2024. Assessment of the Impact of Direct Water Cooling and Cleaning System Operating Scenarios on PV Panel Performance. *Energies* 17(17), DOI: 10.3390/en17174392.

Sribna et al. 2021 – Sribna, Y., Koval, V., Olczak, P., Bizonych, D., Matuszewska, D. and Shtyrov, O. 2021. Forecasting solar generation in energy systems to accelerate the implementation of sustainable economic development. *Polityka Energetyczna – Energy Policy Journal* 24(3), pp. 5–28, DOI: 10.33223/epj/141095.

Staffell, I. and Green, R. 2014. How does wind farm performance decline with age? *Renewable Energy* 66, pp. 775–786, DOI: 10.1016/J.RENENE.2013.10.041.

Stecuła, K. and Brodny, J. 2017. Renewable energy sources as an opportunity for global economic development. [In:] *17th International Multidisciplinary Scientific GeoConference: SGEM 2017*, 27–29 November, 2017, pp. 749–756, DOI: 10.5593/sgem2017H/43/S29.094.

Stecuła, K. and Tutak, M. 2018. Causes and effects of low-stack emission in selected regions of Poland. [In:] *18th International Multidisciplinary Scientific GeoConference: Surveying Geology and Mining Ecology Management, SGEM 2018*, pp. 357–364, DOI: 10.5593/sgem2018/4.2/S19.047.

Turkmen, B.A. and Babuna, F.G. 2024. Life Cycle Environmental Impacts of Wind Turbines: A Path to Sustainability with Challenges. *Sustainability* 16(13), DOI: 10.3390/SU16135365.

Vartiainen et al. 2020 – Vartiainen, E., Masson, G., Breyer, C., Moser, D. and Medina, E.R. 2020. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Progress in Photovoltaics: Research and Applications* 28(6), pp. 439–453, DOI: 10.1002/pip.3189.

Wang et al. 2022 – Wang, W., Xue, Y., He, C. and Zhao, Y. 2022. Review of the Typical Damage and Damage-Detection Methods of Large Wind Turbine Blades. *Energies* 15(15), DOI: 10.3390/EN15155672.

Zarębska, J. and Dzikuć, M. 2013. Determining the environmental benefits of life cycle assessment (LCA) on example of the power industry. *Scientific Journals Maritime University of Szczecin* 34(106), pp. 97–102.

Zhang et al. 2018 – Zhang, J., Cho, H., Luck, R. and Mago, P.J. 2018. Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US. *Applied Energy* 212, pp. 895–908, DOI: 10.1016/j.apenergy.2017.12.091.

Żelazna, A. and Gołębiowska, J. 2015. The measures of sustainable development – A study based on the European monitoring of energy-related indicators. *Problemy Ekorozwoju*.

Marcel Kościelny, Piotr Olczak

Analiza porównawcza LCOE/LCA oraz konserwacji/serwisu odnawialnych źródeł energii w kontekście ograniczeń i zróżnicowania regionalnego w Polsce

Streszczenie

W ostatnich latach wzrost udziału niestabilnych źródeł energii zaliczanych do OZE turbin wiatrowych i instalacji fotowoltaicznych w krajowym (polskim) miksie energetycznym spowodował pojawienie się nowych wyzwań. Wyzwania te obejmują to, co należy zrobić z nadwyżkami w obliczu niskich cen i niewielkich możliwości magazynowania. Rozwiązaniem stosowanym w 2023 i 2024 było przymusowe wyłączanie źródeł w skali krajowego systemu elektroenergetycznego. Zauważono lukę w zakresie metodyki oceny, które instalacje (turbiny wiatrowe czy fotowoltaika) powinny być wyłączane w skali jednego przyłącza energetycznego w formule współdziałania tzw. *cable pooling*. W tym zakresie opracowano metodykę decyzyjną w zakresie wyłączeń mocy wytwórczych opartą na kosztach działania. Zdefiniowano scenariusze mocy zainstalowanej poszczególnych źródeł: instalacji fotowoltaicznej oraz turbin wiatrowych. Następnie wykonano analizę scenariuszy różnych mocy poszczególnych farm w porównaniu do jednej wielkości przyłącza energetycznego. Dowiedziono że w większości przypadków współdziałań farm fotowoltaicznych i farm wiatrowych to farmy wiatrowe powinny być wyłączane jako pierwsze w przypadku przekroczeń mocy z punktu widzenia jednego właściciela dla jednego przyłącza dla tych farm. Osiągnięte wyniki to także głos w dyskusji w sprawie rekompensat za wyłączenia instalacji w skali całego systemu elektroenergetycznego w Polsce. Nie mniej jednak oszacowania w tym zakresie mają szeroki obszar dla pogłębionych analiz dla poszczególnych źródeł z uwzględnieniem różnych uwarunkowań np. wieku urządzeń, warunków lokalnych.

Słowa kluczowe: fotowoltaika, turbiny wiatrowe, koszty obsługi, LCOE, cable pooling