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A simulation-based approach for assessing long-term curtailment levels in variable renewable sources in Poland

Abstract: This study investigates the implications of growing weather-dependent, variable renewable energy sources (VRES) for the Polish power system by 2040, with a particular focus on non-market redispatch. Using a simulation-based approach, six scenarios were developed, combining projected capacities of photovoltaics, onshore wind, and offshore wind with varying electricity demand levels and assumptions on system flexibility. Hourly generation and demand profiles were modeled to estimate both the number of redispatch hours and the curtailed energy volume. Results indicate that without appropriate systemic measures, redispatch could occur for several hundred hours annually, with energy losses reaching tens of TWh. Raising electricity demand in line with ENTSO-E's NT+ and GA projections substantially lowers curtailment. Nevertheless, in the most optimistic GA scenario with an 80% redispatch threshold, curtailment remains above 1300 hours per year. The findings highlight that electrification of end-use sectors, together with flexible demand technologies and thermal storage, is essential to absorb renewable surpluses and mitigate

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curtailment. Without these actions, redispatch may become a barrier to the energy transition in Poland, limiting both system security and the profitability of renewable investments. At the same time, ensuring adequacy requires maintaining dispatchable low-emission generation, including planned nuclear investments, to cover approximately 140 TWh of residual demand, equivalent to around 16 GW of continuous capacity.

Keywords: variable renewable energy sources, simulation, curtailment, power system, adequacy

Introduction

In response to accelerating climate change, the European Union has adopted an ambitious climate and energy policy aimed at achieving climate neutrality, defined as net-zero greenhouse gas emissions. A key element of this strategy is the *Fit for 55* legislative package introduced in 2021, which sets the goal of reducing emissions by at least 55% by 2030 compared to 1990 levels. Among its most important acts is the Renewable Energy Directive (RED III), which requires that renewable energy sources (RES) account for at least 42.5% of the EU energy mix by 2030, with an ambition to reach 45%.

The implementation of these targets has led to the rapid growth of weather-dependent renewables in EU member states, particularly wind power and photovoltaics. While this transformation brings environmental and economic benefits, it also creates challenges for power system operators. Periods of high RES generation combined with low demand, such as sunny holidays, can jeopardize system stability. In such cases, transmission system operators (TSOs) first activate market-based balancing measures, but if these prove insufficient, they resort to non-market redispatch, i.e., forced curtailment of RES generation. International studies show both common drivers and country-specific factors behind redispatch, including grid bottlenecks, regional imbalances between generation and demand, limited system flexibility, and inadequate storage. Comparative analyses highlight diverse experiences: in the US and Germany, redispatch results mainly from transmission constraints, in China, from mismatched locations of generation and consumption, and in Australia and Chile, from limited flexibility and storage (Bird et al. 2016). Quantitative tools such as the Curtailment Energy Share Map reveal that a high share of RES does not always imply high redispatch, as outcomes depend on market design and flexibility (Yasuda et al. 2022). Case studies confirm this: in Ireland, most curtailment stems from minimum conventional generation requirements (Blount et al. n.d.; Hurtado et al. 2023), while in Spain, daytime redispatch is linked to PV overgeneration encouraged by feed-in tariffs (Chaves-Avila et al. 2017). Germany has faced persistently high redispatch costs due to north–south grid constraints and forecast inaccuracies (Joos and Staffell 2018; Schermeyer et al. 2018). Moreover, curtailments often occur in distribution networks rather than transmission, amplifying local effects (Kies et al. 2016; Schermeyer et al. 2018). Studies also show that redispatch significantly reduces effective utilization of RES capacity, underscoring the need for spatially balanced deployment and transmission expansion (Kies et al. 2016). Outside Europe, redispatch is also widespread: in China, more than 260 TWh of renewable energy was curtailed in 2023, mainly due to weak transmission and rigid markets (Li et al. 2015). In Japan, large-scale redispatch first appeared in Kyushu in 2018, caused by rapid PV growth combined with nuclear restarts and limited flexibility (Bunodiere and Lee 2020). Overall, the literature suggests that redispatch is an inevitable feature of energy systems with high RES penetration, but its scale can be mitigated through transmission expansion, storage, demand-side management, and appropriate market reforms. Non-market redispatch has already been observed in Poland since 2023 and is expected to intensify as RES capacity grows towards 2040. Throughout 2023, redispatch was applied on six days: April 23 and 30, May 24, June 2, October 8, and December 25. In 2024, non-market redispatch occurred for a total of 558 hours, and the total volume of curtailed electricity amounted to 731 GWh.

The aim of this study is to assess the future scale of non-market redispatch in Poland, taking into account both RES capacity growth and demand trends. The analysis focuses on three major weather-dependent technologies: onshore wind, offshore wind, and photovoltaics. Specifically, the study addresses the following research questions:

- How will the projected increase in RES capacity affect the scale of redispatch?
- How will demand growth influence the frequency of redispatch events?
- How do meteorological conditions shape redispatch patterns?

The study contributes to the discussion on integrating large-scale renewables into national power systems by quantifying the future redispatch challenge in Poland.

The remainder of this paper is structured as follows: Section 2 outlines the methodology, Section 3 presents the simulation scenarios, Section 4 discusses the results, and Section 5 concludes with key findings and policy implications.

1. Methodology

1.1. Methodology diagram

The assessment of the scale of non-market redispatch of RES units was performed using a simulation-based approach supported by a proprietary algorithm, illustrated in the block diagram in Figure 1. The algorithm operates on an hourly time step over a selected calendar year and comprises the following stages:

1. Hourly resolution of the calculation enables a detailed analysis of both RES generation and electricity demand variability.
2. Installed capacities of the analyzed RES technologies (photovoltaics, onshore wind, offshore wind) were determined for the selected year.

3. Using hourly capacity factors and installed capacities, hourly generation for each technology was calculated and aggregated into a total RES generation profile.
4. An hourly demand profile was developed by scaling the 2023 demand pattern to the assumed annual demand level in the analyzed scenario.
5. Hours in which RES covered at least 60% of demand were identified.
6. For these hours, the surplus generation above the 60% threshold was treated as potentially subject to redispatch.
7. Summing the hourly surpluses across the year yielded the annual volume of curtailed RES generation, interpreted as a simplified measure of system constraints.

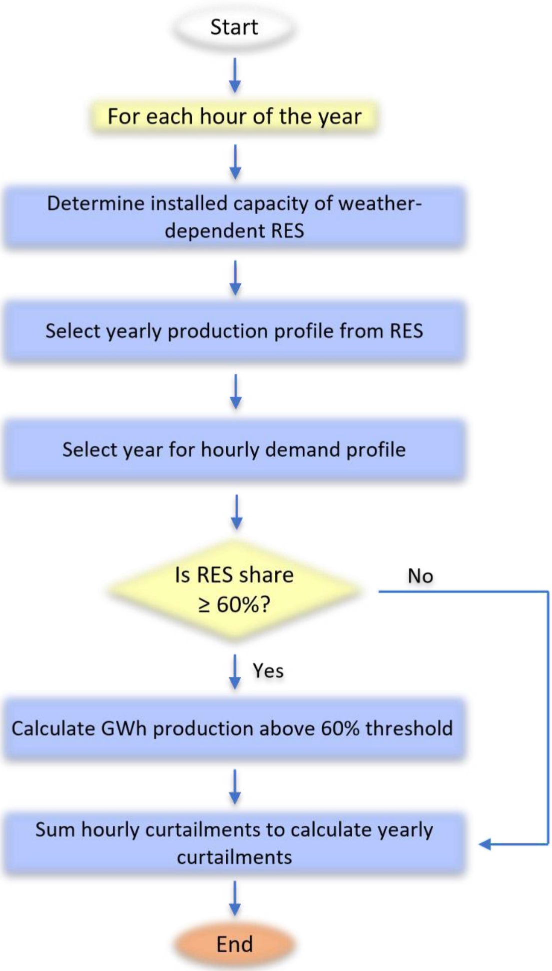

Fig. 1. Flowchart of the methodology for assessing renewable energy production and curtailment

Rys. 1. Schemat blokowy metodologii oceny produkcji energii odnawialnej i ograniczeń

1.2. Input data and assumptions

1.2.1 Description of simulation scenarios

Six simulation scenarios were designed to represent the Polish power system in 2040. The first two assumed projected 2040 RES capacities with electricity demand fixed at the 2023 level. The remaining four were based on ENTSO-E demand forecasts (NT+ and GA scenarios). Each demand variant was combined with two redispatch thresholds: 60%, reflecting limited system flexibility, and 80%, representing an improved ability to integrate variable RES. This approach allowed estimation of the potential benefits of investments in system flexibility. The year 2040 was selected due to the availability of detailed capacity projections.

1.2.2. Hourly capacity factors

Hourly generation data from wind and photovoltaic sources in Poland in 2023 were obtained from daily operational reports published by Polskie Sieci Elektroenergetyczne (PSE). These data provided the reference shape of demand, later used to scale annual projections for 2040 simulations. For photovoltaics and onshore wind, the hourly capacity factor in 2023 was calculated according to the formula:

$$CF_h = \frac{E_h}{P_{inst}} \tag{1}$$

where:

E_h – the electricity production in hour h [MWh],

P_{inst} – the installed capacity [MW].

Since both PV and onshore wind capacity expanded dynamically during 2023, the annual reference value was defined as the weighted average installed capacity P_{inst}:

$$P_{inst} = \frac{\sum_{m=1}^{12} P_m \cdot d_m}{\sum_{m=1}^{12} d_i} \tag{2}$$

where:

P_m – installed capacity in month m,

m – number of days in month m.

Monthly installed capacities are presented in Table 1.

TABLE 1. Installed electrical capacity in photovoltaic and onshore wind power plants in 2023 in every month

TABELA 1. Zainstalowana moc elektryczna w elektrowniach fotowoltaicznych i wiatrowych na lądzie w 2023 r. w poszczególnych miesiącach

Month	PV	Onshore wind
January	12,508.99	8,323.95
February	12,744.26	8,405.82
March	13,021.20	8,573.66
April	13,480.82	8,630.36
May	13,925.80	8,760.50
June	14,268.67	8,857.15
July	14,668.11	8,918.15
August	14,994.19	9,107.80
September	15,627.50	9,136.41
October	16,161.45	9,327.90
November	16,533.00	9,412.76
December	17,057.14	9,428.27

Source: Agencja Rynku Energii SA 2025.

As Poland had no offshore wind capacity in 2023, an alternative data source was required. For this purpose, hourly capacity factors were taken from the ENTSO-E climate dataset (De Felice 2021), which provides simulated generation profiles for offshore wind farms based on 2019 weather conditions.

1.2.3 Future electricity demand

Future demand levels were taken from ENTSO-E's *Ten-Year Network Development Plan* (TYNDP 2024), which sets out long-term scenarios for the European power sector. Two pathways were selected for this study:

- National Trends (NT+): a baseline scenario reflecting currently adopted national energy and climate plans, including NECPs and long-term strategies. It represents the continuation of existing policies and assumes no additional tightening of climate targets.
- Global Ambition (GA): a high-electrification scenario aiming at full climate neutrality by 2050. It assumes deep decarbonization across all sectors, extensive RES deployment, and the rapid development of enabling technologies such as hydrogen production, energy storage, and CCUS.

According to ENTSO-E projections, Polish electricity demand in 2040 will reach 227.13 TWh under NT+ and 293.46 TWh under GA, the latter being more than 25% higher due to accelerated electrification and new loads such as electrolyzers, electric vehicles, and heat pumps.

To construct the hourly demand profiles for 2040, the relative hourly distribution from 2023 was preserved. Each hour's share of annual demand observed in 2023 was applied to the projected annual totals, yielding hourly profiles that maintain realistic temporal variability while reflecting future consumption levels.

1.2.4. Projected installed RES capacity in 2040

Wind energy grew steadily during the 2020–2025 period, from less than 6 GW in January 2020 to just nearly 11 GW at the beginning of 2025. Photovoltaics, in contrast, developed much more dynamically, increasing from 1.6 GW in early 2020 to more than 22 GW five years later. This illustrates the rapid expansion of weather-dependent RES in Poland.

For the long-term horizon, the projected capacities for 2040 were adopted from the report *Analysis for the Power Sector Considering the Changing Political and Economic Situation Following Russia's Invasion of Ukraine*, published in June 2023 by the Ministry of Climate and Environment as part of the pre-consultation process for updating the *National Energy and Climate Plan* (NECP) and *Polish Energy Policy until 2040* (PEP 2040). These projections are considered realistic, as they incorporate the latest political, economic, and market developments.

On this basis, the following installed capacities were assumed in the simulations for 2040:

- photovoltaics: 45 GW,
- onshore wind: 20 GW,
- offshore wind: 18 GW.

Combining these installed capacities with the calculated hourly capacity factors yields the estimated annual electricity generation from RES technologies in 2040 equal to 152.7 TWh (Table 2).

Table 2. Projected annual electricity generation from RES in 2040

Tabela 2. Prognozowana roczna produkcja energii elektrycznej z OZE w 2040 r.

Technology	Installed capacity [GW]	Annual generation [TWh]	Full load hours [h/year]
PV	45	40.8	907
Onshore wind	20	49.6	2,480
Offshore wind	18	62.3	3,456
Total	83	152.7	1,840

2. Results and discussion

The results are presented in two steps. First, a detailed analysis of a selected weekly period is provided in order to illustrate the variability of renewable generation and electricity demand, as well as to visualize moments when RES output approaches or exceeds demand, leading to curtailment. Second, aggregated results for the entire year 2040 are reported, which allow for a comprehensive assessment of the scale and frequency of redispatch under the analyzed scenarios.

For the detailed analysis, the week of April 24–30 was chosen. This period is particularly representative, as curtailment was actually observed in Poland on April 30, 2023. The same week was applied consistently across all scenarios, enabling direct comparison of system performance under identical weather and demand patterns but with different assumptions for installed capacity and annual demand. The actual electricity demand and RES generation in Poland during the week of April 24–30, 2023, is presented in Figure 2.

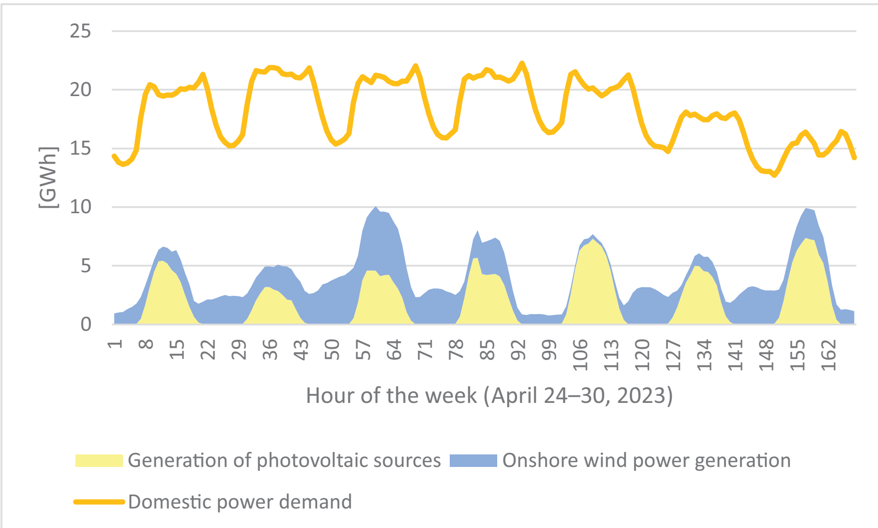

Fig. 2. RES generation and electricity demand profile between 24 and 30 April, 2023

Rys. 2. Profil wytwarzania energii odnawialnej i zapotrzebowania na energię elektryczną w okresie od 24 do 30 kwietnia 2023 r.

Although the total RES output did not exceed demand in this period, on April 30, simultaneous high production from PV and wind coincided with relatively low consumption, triggering curtailment. On that day, RES covered slightly more than 60% of demand. Figure 3 presents the simulated RES generation and electricity demand profile for the NT+ scenario, which assumes increased installed RES capacities and annual demand rising to around 227 TWh by 2040.

As one can see, surplus periods remain, particularly on weekends, when demand is structurally lower. During weekdays, RES penetration is especially high in daytime hours dominated by PV,

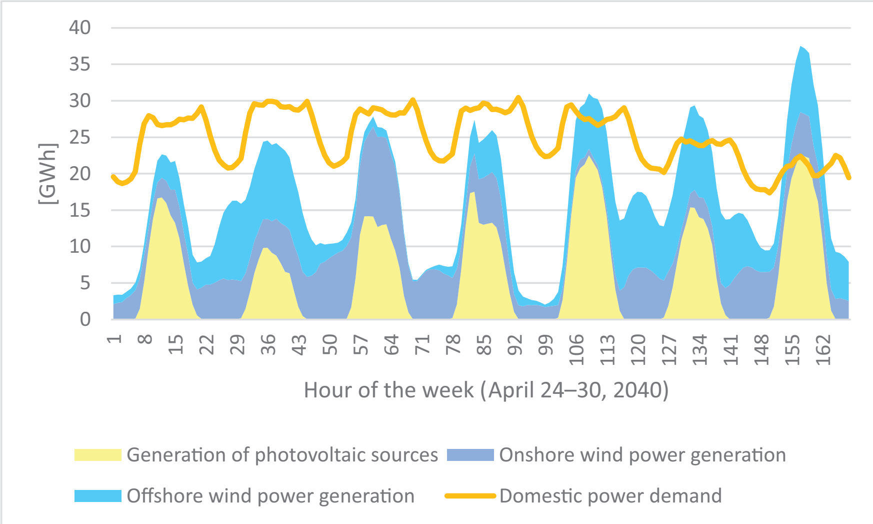

Fig. 3. Weekly RES generation and demand profile in 2040 under the NT+ scenario (April 24–30)

Rys. 3. Tygodniowy profil wytwarzania i zapotrzebowania na energię odnawialną w 2040 r. w scenariuszu NT+ (24–30 kwietnia)

which increases the likelihood of partial curtailment. At the same time, the profile reveals that periods of low RES contribution persist, notably during night hours with weak wind output.

Figure 4 illustrates the results for the GA scenario, where demand grows further to nearly 294 TWh annually.

The additional electrification strengthens system absorptive capacity, meaning that hours of RES surplus are largely confined to weekends. Yet, even in this high-demand scenario, there are frequent hours when RES covers a substantial share of demand, indicating that curtailment risk is not eliminated. Conversely, low-wind nights create periods of weak renewable coverage, underlining the continuing need for flexible balancing resources and backup capacity.

This observation is reinforced by the annual analysis of the share of RES in electricity demand coverage, presented in the form of histograms. These illustrate the frequency of different RES penetration levels throughout the year and highlight the number of hours in which generation exceeded the redispatch thresholds. In the figures, gray bars represent hours below the threshold (no curtailment), while blue bars indicate hours above it (potential redispatch).

Actual 2023 data (Fig. 5) shows that RES rarely exceeded 60% of demand: over half of all hours were below 20%, around 3000 hours fell within the 20–40% range, and only a marginal fraction exceeded 60%.

The picture changes dramatically once the 2040 installed capacities are applied. A higher level of demand helps to mitigate this effect, but still, e.g., in the NT+ scenario (227 TWh in 2040, Fig. 6), redispatch occurs for about 3000 hours annually.

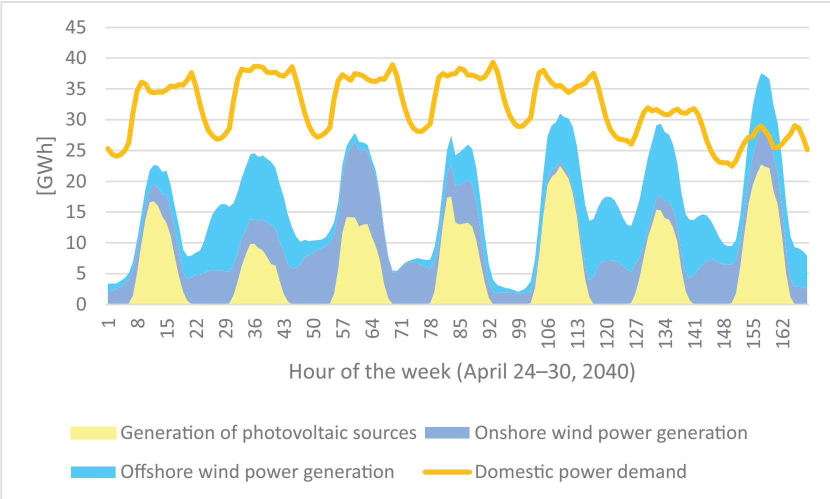

Fig. 4. Weekly RES generation and demand profile in 2040 under the GA scenario (April 24–30)

Rys. 4. Tygodniowy profil wytwarzania i zapotrzebowania na energię odnawialną w 2040 r. w scenariuszu GA (24–30 kwietnia)

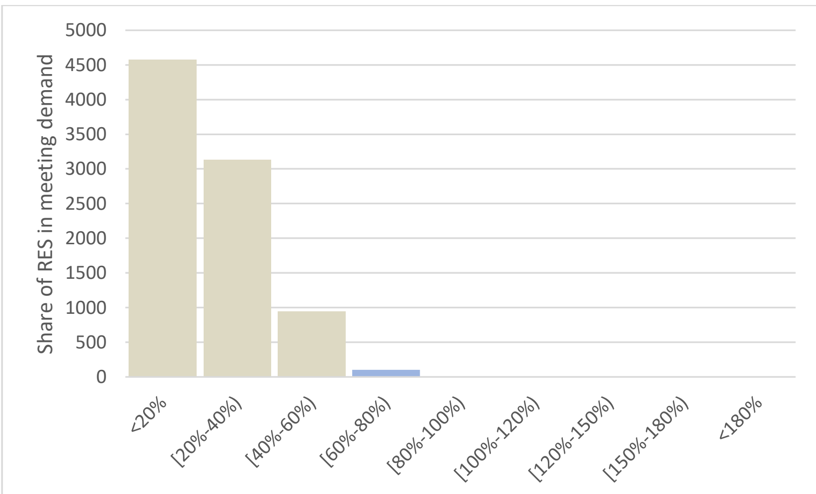

Fig. 5. Histogram of annual hours by RES share in demand coverage, 2023.
Hours with redispatch above the 60% threshold are marked in blue.

Rys. 5. Histogram godzin rocznych według udziału OZE w pokryciu zapotrzebowania, 2023 r.
Godziny z redyspozycją powyżej progu 60% są zaznaczone na niebiesko.

The GA scenario (294 TWh in 2040, Fig. 7) provides the most favorable outcome. Demand growth strongly reduces the scale of redispatch, and only about 1300 hours annually exceed the 80% threshold, and the majority of hours remain in ranges not requiring curtailment.

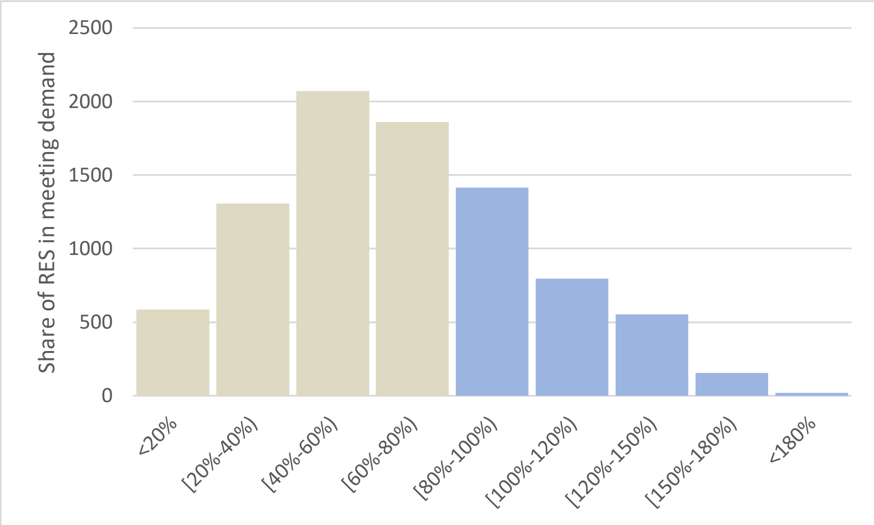

Fig. 6. Histogram of annual hours by RES share in demand coverage, NT+ scenario.
Hours with redispatch above the 80% threshold are marked in blue.

Rys. 6. Histogram godzin rocznych według udziału OZE w pokryciu zapotrzebowania, scenariusz NT+.
Godziny z redyspozycją powyżej progu 80% zaznaczono na niebiesko.

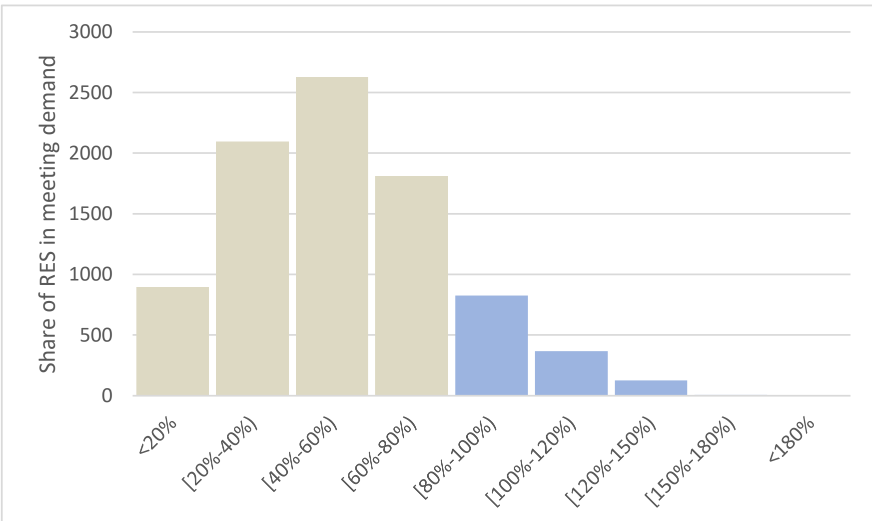

Fig. 7. Histogram of annual hours by RES share in demand coverage, GA scenario 2040.
Hours with redispatch above the 80% threshold are marked in blue.

Rys. 7. Histogram godzin rocznych według udziału OZE w pokryciu zapotrzebowania, scenariusz GA 2040.
Godziny z redyspozycją powyżej progu 80% zaznaczono na niebiesko.

A clear summary of the combined impact of installed RES capacity, electricity demand, and system flexibility on the scale of redispatch is presented in comparative Table 3. It includes actual conditions in 2023 as well as the results of simulations for 2040 under different demand and threshold assumptions.

TABLE 3. Summary of simulation results

TABELA 3. Podsumowanie wyników symulacji

Installed RES capacity [GW]	Redispatch threshold [% of demand met by RES]	Annual electricity demand [TWh]	Curtailment hours [h/year]	Curtailed RES generation [TWh]
14,6 (PV), 8,9 (W_ON), 0 (W_OFF)	60	166.10	106	0.08
14,6 (PV), 8,9 (W_ON), 0 (W_OFF)	80	166.10	3	0.01
45 (PV), 20 (W_ON), 18 (W_OFF)	60	227.13	4,798	38.78
45 (PV), 20 (W_ON), 18 (W_OFF)	80	227.13	2,938	34.17
45 (PV), 20 (W_ON), 18 (W_OFF)	60	293.46	3,140	21.28
45 (PV), 20 (W_ON), 18 (W_OFF)	80	293.46	1,328	15.60

(RES = Renewable Energy Sources, PV = photovoltaics, W_ON = onshore wind, W_OFF = offshore wind).
Source: own study.

Overall, the comparison confirms that while higher electricity demand and system flexibility substantially mitigate the redispatch challenge, they cannot fully eliminate it. Even under the most optimistic assumptions, more than a thousand hours annually still require curtailment, underscoring the importance of complementary measures such as grid expansion, storage deployment, and demand-side management to ensure efficient use of renewable generation.

In addition to the curtailment results, it is worth noting the implications for the overall system balance. Based on the assumed installed capacities and capacity factors, the annual generation from variable RES in 2040 is estimated at approximately 153 TWh (Table 1). In the GA scenario, where curtailment is relatively limited, almost the entire production can be utilized. This implies that the remaining electricity demand must be met by other generating units. Assuming a required complementary generation of around 140 TWh, this corresponds to approximately 16 GW of continuously operating conventional capacity (RES: 153 TWh + Other generation: 140 TWh).

This calculation highlights that even with high RES penetration and increased system flexibility, a significant share of stable generation capacity will still be required to ensure security of supply and cover demand during periods of low renewable output.

Conclusions

This study examined the implications of growing weather-dependent renewable energy capacities for the Polish power system in 2040, focusing on the scale of non-market redispatch. Using a simulation-based approach, scenarios combining projected RES capacities, varying demand levels, and different flexibility thresholds were analyzed. Results show that redispatch will remain a major challenge: even under the optimistic GA scenario with an 80% threshold, curtailment still occurs in over 1,300 hours annually. Demand growth and electrification mitigate the problem but do not eliminate it. Two key requirements emerge. First, further investments in flexibility, such as storage, demand-side management, and sector-coupling technologies, are essential to reduce curtailment and improve efficiency. Controlled electrolyzer operation, smart EV charging, and thermal storage can both raise demand and absorb renewable surpluses at critical times. Second, adequate dispatchable capacity will still be needed to secure supply during periods of low RES output. In the GA scenario, around 140 TWh must be covered by other technologies, equivalent to about 16 GW of continuously operating conventional capacity. To ensure consistency with climate neutrality targets, this residual demand should be met primarily by low-emission and dispatchable sources. In the Polish context, this underlines the importance of pursuing planned investments in nuclear power, complemented by other firm low-carbon technologies. While grid expansion remains important, international experience shows its impact is limited as regional overproduction often persists despite additional transmission capacity (Kozlovas et al. 2024; Stiewe et al. 2025). This underscores that enhancing demand-side flexibility and sector coupling offers more durable solutions than network reinforcement alone.

In conclusion, the study confirms that large-scale RES integration requires not only accelerated deployment but also systemic measures to enhance flexibility, expand sector coupling, and maintain adequacy. Without these actions, redispatch may become a structural barrier to the energy transition in Poland, limiting both system security and the profitability of renewable investments.

The Authors have no conflicts of interest to declare.

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Podejście symulacyjne do oceny długoterminowych ograniczeń generacji w pogodowo zależnych OZE w Polsce

Streszczenie

Niniejsze badanie analizuje implikacje rosnącego udziału pogodowo zależnych odnawialnych źródeł energii (VRES) dla krajowego systemu elektroenergetycznego w Polsce do 2040 roku, ze szczególnym uwzględnieniem zjawiska nierynkowego redysponowania. Wykorzystując podejście symulacyjne, opracowano sześć scenariuszy łączących prognozowane moce zainstalowane fotowoltaiki, lądowej i morskiej energetyki wiatrowej z różnymi poziomami zapotrzebowania na energię elektryczną oraz założeniami dotyczącymi elastyczności systemu. Na podstawie godzinowych profili generacji i zapotrzebowania oszacowano zarówno liczbę godzin z redysponowaniem, jak i wolumen energii podlegającej ograniczeniom. Wyniki wskazują, że bez odpowiednich działań systemowych redysponowanie może występować przez kilkaset godzin rocznie, a straty energii sięgać dziesiątek TWh. Zwiększenie zapotrzebowania zgodnie z projekcjami ENTSO-E (scenariusze NT+ i GA) znacząco ogranicza skalę redukcji generacji. Jednak nawet w najbardziej optymistycznym scenariuszu GA, przy progu redysponowania wynoszącym 80%, konieczność redukcji występuje w ponad 1300 godzinach rocznie. Wyniki wskazują, że elektryfikacja sektorów końcowych wraz z wykorzystaniem elastycznych technologii po stronie popytu oraz magazynów ciepła są niezbędne do absorpcji nadwyżek produkcji z OZE. Bez podjęcia tych działań redysponowanie może stać się barierą dla transformacji energetycznej w Polsce, ograniczając zarówno bezpieczeństwo systemu, jak i opłacalność inwestycji w odnawialne źródła energii. Jednocześnie zapewnienie adekwatności wymaga utrzymania dyspozycyjnych źródeł niskoemisyjnych, w tym planowanych inwestycji jądrowych, aby pokryć około 140 TWh zapotrzebowania rezydualnego, co odpowiada około 16 GW mocy pracującej w trybie ciągłym.

Słowa kluczowe: pogodowo zależne odnawialne źródła energii, symulacja, ograniczanie generacji, system elektroenergetyczny, adekwatność