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Renewable energy transition in Poland: scenario-based analysis of solar and wind integration in the power system

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Abstract

This article examines the current status and development prospects of renewable energy sources (RES) in Poland in the context of the national energy transition and European climate objectives. The study addresses three research questions concerning the role of RES in Poland's energy mix, their development potential, and the main opportunities and barriers to increasing their share. The research combines a literature and data review with scenario-based simulations using the Polish Power System Simulator, based on real weather data from 2015–2023 and electricity demand from 2023. Four scenarios were analysed: the current state, PV-based, wind-based, and combined PV + wind. The results show that RES already play a significant role in Poland's energy sector. In 2023, their share reached 27%, with total installed capacity of 28.6 GW, increasing to 33.3 GW in 2024, dominated by photovoltaics and wind. Despite this growth, coal still accounted for 60.5% of electricity generation in 2023, indicating continued dependence on conventional sources. The analysis identifies solar and wind energy as the main drivers of future RES development. However, further expansion is limited by grid constraints, connection refusals, curtailment, regulatory barriers (including the 700 m rule for wind farms), and insufficient storage and flexibility resources. Simulation results indicate that the combined PV + wind scenario provides the most balanced and resilient system configuration due to complementary generation profiles. Nevertheless, dispatchable backup capacity remains necessary. Achieving a higher RES share is technically feasible but requires diversification, grid modernisation, expanded storage, and stable regulatory conditions.

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1. Introduction

The development of renewable energy sources (RES) represents one of the key challenges and strategic directions for contemporary Poland in the context of energy transition and the pursuit of sustainable development. In light of increasing environmental pressures, the depletion of fossil fuel resources, and the obligations arising from the European Union's climate policy, RES are becoming an integral component of the future structure of the Polish energy sector (Wang and Azam, 2024). In a country whose power generation system still remains largely dependent on coal (Świdyńska, 2024), the accelerated deployment of solar, wind, hydro, geothermal, and bioenergy technologies is of critical importance for enhancing national energy security and reducing greenhouse gas emissions (Wang and Azam, 2024).

Traditional energy resources currently used for power generation are non-renewable and subject to depletion, which necessitates the intensified development and implementation of alternative energy sources (Burek, 2010).

In Poland, the following renewable energy sources are currently utilized (URE, 2025):
- wind energy,
- solar energy,
- hydropower,
- biomass energy,
- geothermal energy.

An increase in the demand for alternative energy sources in the near future would represent a highly desirable development. However, a major factor that continues to constrain the wider adoption of geothermal, solar, hydro, and wind energy technologies is the high capital cost associated with the installation and operation of the necessary infrastructure (Olabi et al., 2023). A major advantage of renewable energy production is its significantly lower environmental impact compared to the generation of energy from fossil fuels (Olabi et al., 2023). This factor may prove decisive in determining the growing popularity of renewable energy sources in the near future.

The development of RES in Poland is imperative, both to reduce greenhouse gas emissions and to ensure compliance with the European Union's climate protection regulations. Increasing the share of RES particularly wind and photovoltaic energy enables a significant reduction in CO_2 emissions (Piasecka et al., 2019, 2020; Walichnowska et al., 2025), which is of critical importance in the context of meeting the objectives of the European Green Deal and the Emissions Trading System (ETS) (Olabi et al., 2023). Since Poland's accession to the European Union, coal consumption has decreased by approximately 33%, while the growing RES share has contributed to a 21% reduction in greenhouse gas emissions compared to 2015 (Piekut, 2021). An additional incentive to accelerate the national energy transition is the introduction, from 2027, of CO_2 emission allowance costs for users of gas installations, which will increase the economic burden associated with the use of natural gas as a transitional fuel (European Commission, 2025). At the same time, Poland must continue to modernize and expand its energy infrastructure to enhance system stability, which is increasingly affected by the variability of weather-dependent RES. In 2023, the share of renewable energy in the national energy mix reached 27%, with a total installed RES capacity of 28.6 GW, primarily driven by the dynamic expansion of photovoltaic installations (Andruszków et al., 2024). Nevertheless, coal remains the dominant source of electricity generation, accounting for 60.5% of total production, although its share is gradually declining (Andruszków et al., 2024). Meeting the European Union's energy and climate objectives and reducing dependence on fossil fuels will require continued investment in renewable energy technologies, as well as the expansion of energy storage systems and cross-border interconnections. These measures are essential to ensure long-term energy security, fulfill international climate commitments, and accommodate future increases in energy demand driven by the electrification of industry, transport, and heating (Andruszków et al., 2024).

Given Poland's obligation to meet the European Union's climate targets, the objective of this paper is to analyse the current RES share in Poland's energy mix, as well as to identify potential opportunities and development directions that would enable the country to meet its energy needs to the greatest possible extent through renewables. The analysis conducted for this study seeks to address the following research questions: (1) What is the current status of renewable energy sources in Poland's energy mix? (2) What are the prospects and possibilities for the development of RES in Poland? (3) What are the opportunities and threats associated with achieving the required RES share in the national energy mix? To answer these questions, an analytical review of the literature and available statistical data on the development of renewable energy sources in Poland was performed. In addition, simulations were carried out to assess the country's energy demand under various scenarios involving different shares of renewable energy installations and energy storage systems in the Polish energy system. The primary objective of the simulation is to compare the operational implications of selected RES development pathways, with particular emphasis on adequacy, variability, curtailment, storage needs, and dependence on dispatchable generation. The scientific contribution lies in a comparative scenario-based evaluation of renewable integration pathways under Polish climatic and demand conditions, rather than in a complete investment or infrastructure planning model.

2. Renewable energy potential in Poland

2.1. Hydropower potential

Water represents a significant store of energy, which is released during its movement. Its defining characteristic is that it always flows from higher to lower elevations, thereby possessing both potential and kinetic energy (Tytko, 2024). There are numerous advantages to harnessing energy from water. Unlike other renewable sources, water does not present significant energy storage challenges; in fact, the construction of dams as energy storage facilities can provide one of the most effective methods for compensating for fluctuations in energy supply from other sources. Moreover, hydroelectric power plants demonstrate high conversion efficiencies, often exceeding 85% (Lewandowski, 2012).

Hydropower potential in Poland, although relatively limited compared to other renewable energy sources, plays an important role in the national electricity system and contributes to the country's energy stability and security. The history of hydropower in Poland dates back to the 19th century, when the first hydroelectric projects were established, and during the interwar period, Poland was a regional leader in Central and Eastern Europe. Currently, hydropower accounts for approximately 3% of the national energy mix (Andruszków et al., 2024).

Poland's hydropower resources are estimated at approximately 13.7 TWh per year. The country hosts more than 700 small hydro power plants (SHPP), which collectively represent about 0.5% of the installed capacity in the national electricity system. Most of these facilities are located on smaller rivers and reservoirs, with individual capacities not exceeding 10 MW. Across Europe, approximately 91% of both existing and planned hydropower plants are small-scale facilities, which may be owned by energy companies, local communities, or private investors (Andruszków et al., 2024).

One of the primary challenges for the development of hydropower in Poland is the variability of water flows, which is further exacerbated by changing climatic conditions, including periods of drought and episodes of intense rainfall (Tytko, 2024). Therefore, effective management of water retention in reservoirs is essential to mitigate fluctuations in water availability for energy production. Furthermore, many existing hydropower plants require modernization to ensure their performance aligns with the European Union's targets for the share of renewable energy sources in the national energy mix (Andruszków et al., 2024).

In 2022, an inter-ministerial team was established to develop projects for new pumped storage power plants with a combined capacity of up to 6 GW (Andruszków et al., 2024). A notable example is the 'Młoty' project in Bystrzyca Kłodzka, which will become the largest pumped storage power station in Poland, with a planned capacity of 1050 MW. This project is expected not only to enhance the stability of the national energy system, but also to provide regional flood protection and generate new employment opportunities. Construction is scheduled for completion by 2030 (Andruszków et al., 2024).

An inventory conducted by the National Water Management Authority indicated that there are over 14000 damming facilities in Poland, of which only 4.5% are utilized for energy generation (Andruszków et al., 2024). This highlights the considerable untapped potential for hydropower development in the country. However, fully realizing this potential will require sufficient funding and investment in modern technologies and infrastructure.

2.2. Wind energy potential

Wind energy is another form of power that has been harnessed by humans for centuries. The potential of wind energy in Poland is highly promising and constitutes a key element of the country's ongoing energy transition. Both onshore and offshore wind power have the capacity to play an increasingly significant role in the national energy mix. With appropriate legal frameworks and adequate financial support, onshore wind farms could become the second-largest source of electricity generation in the future, surpassing lignite (Andruszków et al., 2024).

Poland's updated energy policy projects that the installed capacity of onshore wind turbines will reach 14.5 GW by 2030, while the National Energy and Climate Plan anticipates nearly 16 GW (Ministerstwo Klimatu i Środowiska, 2019). According to the Polish Wind Energy Association (PWEA), this figure could increase to as much as 18 GW by 2030 if the full potential of onshore wind resources is exploited (TPA Poland/Baker Tilly TPA, 2025). However, the expansion of this sector faces several challenges, particularly related to location constraints. Current regulations impose a minimum distance of 700 metres between wind turbines and residential buildings, significantly limiting the number of viable sites and reducing the potential installed capacity by approximately 60-70%. A reduction of this distance to 500 metres could potentially double the available area from around 2% to 4% of Poland's total land area offering tangible benefits for both investors and local governments (Andruszków et al., 2024).

Another significant challenge is the complex and time-consuming permitting process for wind farm development. At present, obtaining the necessary permits can take approximately ten years, although there is potential to shorten this period to around three years through regulatory simplification. Furthermore, substantial investment in transmission infrastructure is required to ensure the effective integration of wind energy into the national power grid while preventing excessive cost burdens on end consumers (TPA Poland/Baker Tilly TPA, 2025).

Poland possesses substantial potential for the development of offshore wind energy. Numerous initiatives have been launched to support the construction of wind farms in the Baltic Sea since 2023. Planned auctions account for a total installed capacity of 12 GW, with capacity expected to increase to 18 GW by 2040 (Ministerstwo Klimatu i Środowiska, 2019). In 2024, installed wind power capacity exceeded 10 GW (Wójcik, 2025). In 2023, specific locations for offshore wind farm projects were also designated, with a total installation potential estimated at 9.4 GW. As part of a strategic initiative to unlock Poland's offshore wind potential, investments valued at approximately 40 billion PLN are planned, which are expected to generate an added value 178 billion PLN and create up to 100000 new jobs (Andruszków et al., 2024).

A wind turbine blade manufacturing plant is scheduled to open in Szczecin in 2026, alongside a wind tower production facility, while large-scale steel structures for offshore wind installations are planned to be manufactured in Gdańsk (PWEA, 2024).

In 2023, the installed capacity of onshore wind farms in Poland increased by 8.5%, while total wind power generation rose from 12.3 TWh in 2019 to 22.1 TWh in 2023. By the end of 2023, the country had 1413 operational installations with a combined capacity of 9.56 GW (Andruszków et al., 2024). Although Poland does not yet have any operational offshore wind farms, the implementation of planned offshore projects holds substantial potential for future growth in national energy production.

2.3. Geothermal energy potential

The Earth's subsurface is increasingly recognized as a valuable source of geothermal energy. As a planet with a hot interior, the Earth contains an immense amount of thermal energy, part of which is transferred toward the surface through hot springs and the thermal conductivity of rocks. From there, the heat gradually dissipates into the atmosphere (Lewandowski, 2012).

The potential of geothermal energy in Poland is considerable, although its current contribution to the country's renewable energy mix remains relatively modest. Geothermal energy is derived from the Earth's interior in the form of hot water or steam and can be utilized for both heat generation and electricity production (Tytko, 2024). In Poland, geothermal resources are primarily located at depths ranging from 700 to 3000 metres, with water temperatures typically varying between 20°C and 100°C (Mięsikowski, 2014).

The most favourable conditions for the utilisation of geothermal energy in Poland occur within the Podhalańska Basin, the Grudziądz-Warsaw region, and the vicinity of Szczecin. Geothermal resources are also present in several major urban areas, including Warsaw, Poznań, Płock, Toruń, and Szczecin. However, the extraction and effective use of geothermal energy in these locations are constrained by dense urbanisation and the industrial character of these regions (Lewandowski, 2012; Mięsikowski, 2014).

The total geothermal energy potential in Poland is estimated at approximately 1512 PJ per year, which corresponds to around 30% of the country's thermal energy demand (Mięsikowski, 2014). Despite this considerable potential, geothermal energy currently accounts for only about 0.3% of Poland's renewable energy production. In 2020, Poland ranked 14th among European Union member states in terms of the number of geothermal installations. During that year, geothermal heat production amounted to 1.07 PJ, representing only 0.4% of the district heat supplied to consumers (Andruszków et al., 2024).

In 2022, Poland had seven operational geothermal installations, yet development plans are ambitious. By 2030, 58 new projects are planned, which would achieve a total installed capacity of 230 MWt and generate approximately 2.5 PJ of heat (Andruszków et al., 2024). Combined with existing facilities, geothermal energy could satisfy around 1.5% of the country's district heat demand. By 2040, the installed capacity is projected to increase to 290 MWt, and by 2050, geothermal energy could provide up to 720 PJ of heat. This expansion would result in substantial financial and environmental benefits, including a reduction in CO_2 emission costs of approximately 69 billion PLN (Andruszków et al., 2024).

The primary challenges to the development of geothermal energy in Poland include technical issues such as corrosion, scaling, and mineral deposition, as well as the need for proper monitoring and management of the extracted water (Tytko, 2024). Nevertheless, geothermal energy is an environmentally sustainable and socially acceptable technology, which supports its further expansion. Utilising geothermal heat can reduce emissions in the heating sector, thereby improving air quality and contributing to the health and well-being of local communities.

2.4. Biomass energy potential

Biomass energy is an environmentally beneficial form of renewable energy produced from organic raw materials of plant and animal origin. Through anaerobic digestion a controlled biological process involving the decomposition of plant or animal waste, as well as dried sewage sludge biogas is generated. After appropriate purification and treatment, this biogas can be used for energy production (Lewandowski, 2012).

Poland is considered one of the leading markets in the European Union in terms of biomethane production potential, ranking fifth overall. Estimates indicate that national production could reach up to 8 billion cubic metres per year, which would be sufficient to meet nearly half of the country's natural gas demand (Sienkiewicz et al., 2024). This significant potential results from Poland's favourable resource base the nation is among the largest food producers in Europe, and its agricultural sector generates substantial quantities of organic waste that can be efficiently converted into biogas through advanced anaerobic digestion technologies (Ciuła et al., 2023).

Currently, there are 166 operational biogas installations in Poland, primarily agricultural biogas plants, with a total installed capacity exceeding 156 MW and an annual biogas production volume of more than 640 million cubic metres (Sienkiewicz et al., 2024). In 2023, electricity generation from agricultural biogas exceeded 920 GWh, representing a 15% increase compared to the previous year. A significant portion of the biogas produced approximately 415 million cubic metres was utilised for electricity generation, while the production of digestate reached around 5.2 million tonnes (Bednarek and Klepacka, 2024). The growing interest in biogas production is driven by rising fossil fuel prices and the increasing need to meet the European Union's decarbonisation and energy transition objectives.

Despite these positive trends, the biogas sector in Poland continues to face significant barriers to development. Investors must still navigate complex administrative procedures, including lengthy environmental permitting processes and limited access to the national electricity grid, both of which hinder the implementation of new projects (Bednarek, Klepacka and Siudek, 2023). Experts emphasize that the modern biogas technologies currently available in Poland such as the Dynamic Biogas system demonstrate high efficiency and competitiveness compared to older solutions developed in Western Europe. This represents a considerable advantage, particularly in light of the relatively limited financial support that the sector has received in recent years (Bednarek, Klepacka and Siudek, 2023).

The Biogas Special Act of 2023 and the Energy for Villages programme are expected to significantly accelerate investment in the sector, particularly through the availability of loans covering up to 100% of project costs and grants of up to 65% of eligible expenditures (Andruszków et al., 2024). A notable example of large-scale investment activity is PGNiG BioEvolution, which aims to achieve an annual biogas production of 1 billion cubic metres by 2030. The company's projects include biogas plants capable of upgrading raw biogas into bioLNG and bioCNG (Sienkiewicz et al., 2024). Owing to the synergy between energy generation and waste management, the Polish biogas sector has the potential to become a stable pillar of the green energy transition, contributing to job creation and the advancement of a circular economy (Sienkiewicz et al., 2024).

2.5. Solar energy potential

Solar energy, commonly referred to as solar power, is considered one of the safest and most sustainable energy sources available. The amount of solar radiation reaching the Earth's surface is immense and exceeds global energy demand many times over; however, its significant spatial and temporal dispersion poses a major challenge to effective utilisation (Lewandowski, 2012). Solar energy can be converted into electricity through photovoltaic systems or into thermal energy using solar collectors (Tytko, 2024).

Photovoltaic (PV) cells are specialised semiconductor devices used to convert solar radiation directly into electrical energy. Their structure is typically based on a flat-plate design composed of two layers forming a p-n junction (Tytko, 2024). When solar photons strike the cell surface, they generate electron-hole pairs, resulting in the production of direct current (DC), which can subsequently be supplied to electrical circuits or stored in batteries (Tytko, 2024).

This process is known as the photovoltaic effect. An essential component of every photovoltaic system is the inverter, a device responsible for converting direct current (DC) generated by the solar modules into alternating current (AC) with parameters suitable for transmission through building electrical circuits and for powering electrical appliances (Lewandowski, 2012).

The potential for solar energy development in Poland is considerable, as demonstrated by the rapid expansion of PV sector in recent years. In 2023, photovoltaics represented the primary driver of growth within the country's renewable energy market, accounting for approximately 60% of the total installed renewable energy capacity. By the end of 2023, the cumulative installed PV capacity had reached 17 GW, reflecting a 38% increase compared to the previous year (Andruszków et al., 2024).

The prosumer segment comprising micro-installations primarily located on residential, service, and commercial buildings has played a pivotal role in driving the expansion of the photovoltaic market in Poland. By the end of 2023, the total installed capacity of prosumer micro-installations reached 10.7 GW, representing approximately 66% of the country's overall photovoltaic capacity (Office, no date). In total, around 1.4 million such installations were in operation nationwide (Office, no date). Although the annual growth rate of the prosumer segment declined slightly in 2023, from 69% to 43% year-on-year, it continues to make a substantial contribution to the expansion of Poland's photovoltaic capacity (Andruszków et al., 2024).

There is also increasing potential for small-scale PV installations, defined as systems with capacities up to 1 MW that do not require a licence. These installations accounted for approximately 24% of total PV capacity, reaching 4.1 GW. In parallel, larger PV farms with capacities exceeding 1 MW are being developed across Poland. In 2023, 80 such utility-scale farms, with a combined capacity of 0.77 GW, were connected to the grid, reflecting a growing market share for larger PV projects (Andruszków et al., 2024).

Geographically, the largest concentration of photovoltaic projects in Poland is found in the Wielkopolskie Voivodeship, which hosts 557 installations (URE, 2025). his region also leads in terms of building permits, with 272 projects approved, representing a total capacity of 0.7 GW. The development of large-scale PV projects, particularly those exceeding 50 MW, constitutes nearly half of the country's potential for future investment in solar energy (Andruszków et al., 2024).

However, the development of solar energy in Poland faces certain limitations associated with grid infrastructure. In 2023, power companies refused connection conditions in over 7000 cases, highlighting the challenges of integrating a large number of variable, weather-dependent energy sources into the national electricity system (Plebański, 2024). Nevertheless, the continued systematic growth of renewable energy sources, particularly solar power, remains crucial for advancing Poland's energy transition.

3. Contribution renewable energy to Poland's energy mix

3.1. Electricity production

According to data from the "Raport transformacji energetycznej Polski 2025", total electricity production from renewable energy sources in 2024 amounted to 49.8 TWh (Table 2).

Table 2. RES electricity production by source type in 2024 (Raport transformacji energetycznej Polski 2025)

RES [-]	Energy production [TWh]
Hydro energy	2.10
Wind energy	24.50
Biomass energy (+biogas)	7.90
Solar energy	15.20
Other RES	0.10

The largest contribution came from wind energy, which generated 24.5 TWh, representing almost half of all RES-based electricity production. Solar energy was the second-largest source, producing 15.2 TWh, reflecting the rapid expansion of photovoltaic installations in recent years (Raport transformacji energetycznej Polski 2025).

Electricity generation from biomass and biogas reached 7.9 TWh, reaffirming their role as stable, dispatchable renewable sources. In contrast, hydropower contributed 2.1 TWh, reflecting the limited hydrological potential in Poland. Other renewable sources produced an additional 0.1 TWh, a marginal share in the overall structure (Raport transformacji energetycznej Polski 2025).

The structure of renewable electricity production in 2024 (Fig. 1) demonstrates a strong dominance of wind and solar energy, which together account for approximately 80% of all RES generation.

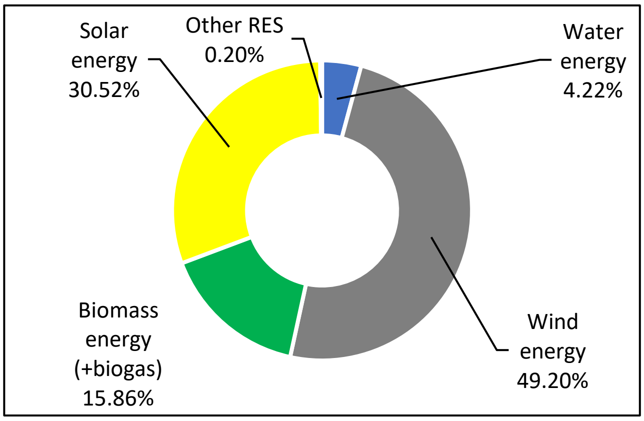

Fig. 1. RES electricity production structure in 2024 (Raport transformacji energetycznej Polski 2025)

This shift toward weather-dependent RES highlights Poland's progressing energy transition, while simultaneously emphasising the increasing need for investments in grid flexibility, energy storage and balancing (Raport transformacji energetycznej Polski 2025).

3.2. RES installed capacity

In 2024, the total installed capacity of renewable energy sources in Poland reached 33.3 GW, showing a significant expansion compared to previous years (Table 1). Photovoltaics remained the fastest-growing technology, with installed capacity reaching 20.9 GW, making it the dominant component of the RES mix. This reflects both high investment activity and the increasing popularity of prosumer and utility-scale PV installations (Raport transformacji energetycznej Polski 2025).

Table 1. Installed RES capacity by source type in 2024 (Raport transformacji energetycznej Polski 2025)

RES [-]	Installed capacity [GW]
Hydro energy	0.60
Wind energy	10.60
Biomass energy (+biogas)	1.10
Solar energy	20.90
Other RES	0.10

Wind energy constituted the second-largest RES technology, with an installed capacity of 10.6 GW, confirming its strategic importance in Poland's transition toward low-carbon electricity generation. Biomass and biogas installations reached a combined capacity of 1.1 GW, maintaining their role as stable, dispatchable RES technologies capable of supporting system flexibility (Raport transformacji energetycznej Polski 2025).

In contrast, hydropower installations accounted for only 0.6 GW, consistent with the country's limited hydrological potential. The remaining 0.1 GW of capacity was classified as other RES technologies (Fig. 2).

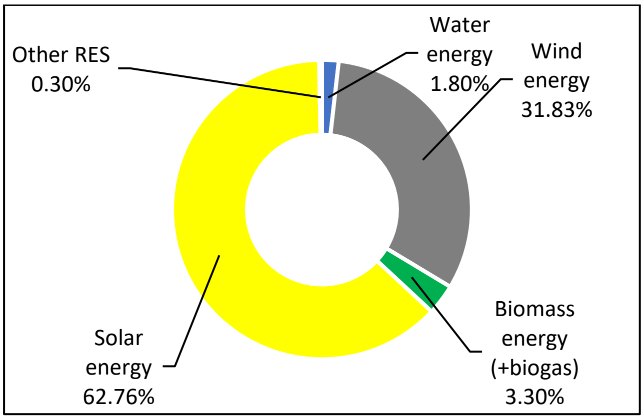

Fig. 2. Installed RES capacity structure in 2024 (Raport transformacji energetycznej Polski 2025)

The 2024 capacity structure clearly demonstrates the increasing dominance of solar and wind energy, which together represent more than 94% of total installed RES capacity. This trend confirms the rapid shift toward scalable, weather-dependent renewable technologies and underscores the growing importance of modernising grid infrastructure and expanding energy storage systems to maintain system stability (Raport transformacji energetycznej Polski 2025).

4. Analysis RES development opportunities in Poland

4.1. Analysis methodology

A current challenge in electricity production from RES is the inherent variability and intermittency of generation. Recently, the increasing share of photovoltaic installations in the power system, combined with periods of high wind energy production, has led to temporary shutdowns of these facilities when generation exceeds instantaneous demand. This situation is disadvantageous because it results in lost renewable energy potential and generates economic losses for investors. Consequently, the expansion of RES cannot be effectively pursued without detailed analyses of their integration into the electricity system. To evaluate future prospects for RES development in Poland and assess their impact on the national power system scenario-based simulations were performed. This does not constitute a full techno-economic optimisation of Poland's energy transition or a detailed grid-engineering design study. Its primary objective is to compare the operational implications of selected renewable energy development pathways, with particular emphasis on adequacy, variability, curtailment, storage needs, and dependence on dispatchable generation. Accordingly, the storage and infrastructure parameters adopted in the simulations should be interpreted as scenario assumptions used to evaluate system flexibility, rather than as optimised implementation values. A detailed economic assessment, including LCOE, CAPEX/OPEX structure, profitability, and cost-benefit analysis, remains beyond the scope of the present work and should be addressed in future research. Similarly, the present analysis is not intended to provide a detailed grid-engineering design of transmission and distribution system expansion, but rather to identify system-level technical constraints relevant to large-scale RES integration.

Simulations were conducted using the Polish Power System Simulator, developed by the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju, 2023). The simulator is a sophisticated tool designed for modelling and analysing the performance of complex energy systems. It enables the evaluation of various scenarios related to energy production, distribution and consumption, accurately representing the behaviour of key system components such as power plants, transmission networks and demand nodes. By simulating events such as equipment failures, demand fluctuations or the integration of renewable energy sources, the tool supports research, planning and the operation of a safe, reliable and efficient electricity network (Narodowe Centrum Badań i Rozwoju, 2023).

However, the simulation framework applied in this study operates at the national system level, does not represent a full nodal or line-constrained transmission model. Although the model includes transmission losses as a system parameter (table 3), it does not resolve congestion on specific transmission corridors or substations. Therefore, the results should be interpreted as a comparative operational assessment of RES development pathways rather than as a detailed network-feasibility study or a complete transmission expansion plan.

Using real Polish weather data from 2015-2023 and actual electricity demand from 2023, the simulator compares renewable energy production with total national energy demand, including transport, heating, and other sectors. The input datasets used in the simulations are publicly available on the simulator's website (https://symulatorsystemuenergetycznego.ncbr.gov.pl/data). The simulator does not analyse price fluctuations or demand responses that could arise from other factors, such as the level of energy storage filling or weather forecasts. It also determines the amount of methane required from dispatchable sources to ensure uninterrupted energy supply. This demand is evaluated relative to Poland's biomethane potential, estimated at several billion cubic metres from waste biomass, or several dozen billion cubic metres when a moderate share of energy crops is included. In addition, the simulator accounts for the operation of electricity and thermal energy storage systems and includes electrolysers producing hydrogen for sectors that cannot be directly electrified, such as aviation or heavy military equipment (Narodowe Centrum Badań i Rozwoju, 2023).

This simulator has these scenarios (Narodowe Centrum Badań i Rozwoju, 2023):

- "Polish energy system - current state",
- "Polish energy system - RES + dispatchable sources",
- "Polish energy system - RES + dispatchable sources + storage",
- "Electrification of road transport and heat",
- "Electrification of road transport and heat + energy sources (at maximum)",
- "Energy efficiency + energy Sources (at maximum)",
- "Energy efficiency + energy sources 100% RES",
- "Carbon-free economy - 100% RES"
- "Carbon-free economy - 100% nuclear"
- "Carbon-free economy - RES + nuclear mix".

"Polish energy system - current state" scenario illustrates Poland's existing energy mix, which remains heavily dependent on conventional fossil fuels, including coal and natural gas. This scenario allows users to examine the operation of the current system, identify its primary energy sources, and evaluate the associated emissions. It serves as a benchmark for comparing future energy scenarios and assessing the potential impacts of energy system transformations on both the national energy balance and environmental performance (Narodowe Centrum Badań i Rozwoju, 2023).

"Polish energy system - RES + dispatchable sources" scenario represents an energy system that is partially based on renewable energy sources, such as wind and solar, while being supported by conventional dispatchable units. These dispatchable sources can be activated when generation from RES declines, ensuring system stability and reliability of energy supply. The scenario evaluates the potential role of dispatchable sources and determines their operational requirements in a system where renewable energy constitutes the primary source of electricity generation (Narodowe Centrum Badań i Rozwoju, 2023).

"Polish energy system - RES + dispatchable sources + storage" scenario incorporates energy storage technologies, including batteries and thermal energy storage systems. The objective of this scenario is to enhance system flexibility and reduce reliance on dispatchable generation. Energy storage enables surplus electricity generated by renewable energy sources to be stored and subsequently used during periods of low production, thereby lowering both emissions and operational costs (Narodowe Centrum Badań i Rozwoju, 2023).

"Electrification of road transport and heat" scenario simulates the large-scale transition to electric mobility and the electrification of heating systems. It evaluates how the resulting increase in electricity demand from electric vehicles and electric heating installations will impact the Polish energy system. The simulation also considers the required investments in energy infrastructure necessary to accommodate these additional loads while maintaining system reliability and efficiency (Narodowe Centrum Badań i Rozwoju, 2023).

"Electrification of road transport and heat + energy sources (at maximum)" scenario extends Scenario 3 by assuming the maximum feasible expansion of renewable energy sources (RES) to meet the increased electricity demand resulting from the electrification of transport and heating systems. This scenario evaluates how a fully optimised RES-based system can support the transition while addressing the new challenges of grid balancing (Narodowe Centrum Badań i Rozwoju, 2023).

"Energy efficiency + energy sources (at maximum)" scenario incorporates advanced energy efficiency measures alongside RES expansion. The implementation of these strategies aims to reduce overall energy consumption, thereby enhancing sustainability within a system predominantly supplied by renewable energy (Narodowe Centrum Badań i Rozwoju, 2023).

"Energy efficiency + 100% RES energy sources" scenario envisions the complete elimination of CO_2 emissions by meeting all energy demand exclusively through renewable sources while maximising energy efficiency. This scenario explores the technological and systemic solutions required to achieve full energy independence with minimal energy consumption (Narodowe Centrum Badań i Rozwoju, 2023).

The "Zero carbon economy - 100% RES" scenario simulates a system in which all electricity is generated from renewable sources, such as wind and solar. It focuses on the challenges posed by the seasonal variability of RES generation and the need to manage periods of energy surplus and deficit (Narodowe Centrum Badań i Rozwoju, 2023).

"Zero carbon economy - 100% nuclear" scenario represents an alternative model in which all electricity demand is met through nuclear power. The simulation assesses supply stability, energy security, and the financial implications of investing in nuclear technology, while also considering potential environmental benefits and challenges (Narodowe Centrum Badań i Rozwoju, 2023).

"Carbon-free economy - RES + nuclear mix" examines a hybrid system supplied by both renewable sources and nuclear power. It evaluates how combining these technologies can leverage their respective advantages to ensure sustainability, reliability, and a carbon-free energy supply (Narodowe Centrum Badań i Rozwoju, 2023).

Each scenario enables users to explore different system configurations and evaluate which solutions are most effective in supporting Poland's energy transition.

Simulation parameters are defined in table 4 in the Appendix.

Considering development trends and the potential of individual energy sources, the analysis was conducted for four distinct development scenarios:

- "Current state"
- "PV-based"
- "Wind-based"
- "PV + wind-based"

These scenarios were selected because wind and solar energy represent the most readily available renewable resources in Poland. Their selection is motivated by the need to evaluate potential pathways for renewable energy development while considering technical, economic, and environmental constraints. Photovoltaics and wind power are two key renewable energy sectors that differ in terms of cost structure, resource availability, generation profiles, and impact on power system operation. Analysing each scenario individually, as well as in combination, enables the identification of potential investment strategies, the assessment of grid balancing challenges, and the evaluation of the benefits resulting from diversification of renewable energy sources.

For all scenarios except the "Current state" case, the installed capacities of generation sources were calculated using the standard capacity factor formula (https://en.wikipedia.org/wiki/Capacity_factor):

$$\boldsymbol{P} = \frac{\boldsymbol{E_c}}{\boldsymbol{8760\ h \cdot CF}} \tag{1}$$

where: P - power [GW], E_c - annual energy consumption [GWh], CF - capacity factor [-] (for PV - 0.12, for wind - 0.30)

The required installed capacity was determined by rearranging the capacity factor formula to ensure that annual electricity production corresponds to the assumed level of energy demand. In this approach, annual energy output is defined as the product of installed capacity, capacity factor, and the number of hours in a year. Consequently, installed capacity was estimated by dividing the target annual electricity generation by the product of the assumed capacity factor and total annual operating hours. This method ensures internal consistency between assumed demand levels and generation capacity in each scenario.

The differences between the scenarios arise from the distinct characteristics of these technologies: solar PV operates efficiently primarily during daylight hours and under sufficient sunlight, whereas wind turbines can generate electricity at night and during periods of high wind. Exploring these configurations allows for the assessment of system stability and energy efficiency, while also preparing for potential technological and climatic variations.

Table 3 presents the input data used for simulations in each scenario. The first scenario is based on the current "Polish energy system - current state", while the remaining scenarios are derived from modifications of "Polish energy system - current state".

The "Current state" scenario reflects the present condition of the Polish energy system. The installed capacities of wind turbines and photovoltaic installations are based on data from the Raport transformacji energetycznej Polski 2025, while the storage capacity of pumped-storage power plants and electric car share is taken from the publicly available sources (https://wysokienapiecie.pl/82421-pge-tauron-i-orlen-zbuduja-elektrownie-szczytowo-pompowe/), (https://elektromobilni.pl/rekordowy-pazdziernik-w-historii-polskiej-elektromobilnosci-91-udzialu-w-rynku-kamien-milowy-na-horyzoncie/). Parameters marked with the symbol "N" in Table 3 were excluded from the simulation for methodological reasons. First, several of these parameters refer to technologies that are not currently deployed in Poland at a system-relevant scale, such as offshore wind farms, nuclear power plants, large-scale electrical energy storage, thermal energy storage systems (PTES), and electrolysers for hydrogen production. Although these technologies appear in strategic plans and long-term policy documents, their actual installed capacities, operational characteristics, and system integration remain uncertain. Including assumed values for such technologies would introduce speculative elements and reduce the robustness of the baseline scenario.

Second, parameters related to industrial heat demand, industrial heat storage, waste heat recovery, and district heating integration were not included due to the lack of consistent, high-resolution national data. While aggregate energy consumption statistics for industry exist, detailed information on hourly heat demand profiles, storage capacities, and the technically and economically recoverable share of industrial waste heat is not publicly available. Modelling these elements would therefore require additional assumptions beyond the scope of a reference scenario.

Third, variables describing structural changes in heating systems and end-user technologies, such as the share of consumers connected to district heating networks, the share equipped with individual heat storage, or the distribution between ground-source and air-source heat pumps, were omitted. These parameters depend strongly on regional infrastructure, building characteristics, and long-term renovation pathways, which are subject to significant uncertainty and spatial variability.

Finally, demand-side flexibility mechanisms, including demand elasticity and advanced demand response, were not activated in the "Current state" scenario. Although demand-side management is expected to play an important role in future energy systems with high shares of variable renewable energy, such mechanisms are not yet implemented in Poland at a scale that would justify their inclusion in a baseline representation of the current system.

Table 3. Input data for simulation

Input data	Scenario			
	Current state	PV-based	Wind-based	PV + wind-based
Off-shore wind [GW]	0.0 (N)	0.0	0.0	0.0
On-shore wind [GW]	10.6 (R)	0.0	162.0	81.0
Photovoltaics [GW]	20.9 (R)	404.0	0.0	202.0
Atom power plant [GW]	0.0 (N)	0.0	0.0	0.0
Thermal power plants operating in cogeneration percentage [%]	40.0 (S)	40.0	40.0	40.0
Double-sided panels share in east-west orientation [%]	0.0 (S)	0.0	0.0	0.0
Modern turbines share [%]	0.0 (S)	0.0	0.0	0.0
Loss during transmission [%]	5.0 (S)	5.0	5.0	5.0
Gas power plants efficiency [%]	50.0 (S)	50.0	50.0	50.0
Stationary batteries [GWh]	0.0 (N)	6000.0	3000.0	3000.0
Car batteries [GWh]	0.0 (N)	0.0	0.0	0.0
Pump storage power plants [GWh]	58.97 (R)	78.47	78.47	78.47
Large PTES [GWh]	0.0 (N)	0.0	0.0	0.0
Small domestic [GWh]	0.0 (N)	0.0	0.0	0.0
Heat demand in industry [%]	0.0 (N)	0.0	0.0	0.0
Heat demand in industry - heat storage, capacity [GWh]	0.0 (N)	0.0	0.0	0.0
Heat demand in industry - customers with storage facilities percentage [%]	0.0 (N)	0.0	0.0	0.0
Waste heat from industry transferred to district heating networks percentage [%]	0.0 (N)	0.0	0.0	0.0
Heat consumers connected to the network [%]	0.0 (N)	0.0	0.0	0.0
Consumers with heat storage facilities, including the CH [%]	0.0 (N)	0.0	0.0	0.0
Heat consumers - without heat storage facilities [%]	100.0 (S)	100.0	100.0	100.0
Demand [%]	100.0 (S)	100.0	100.0	100.0
Road transport [%]	10.0 (R)	10.0	10.0	10.0
Base demand for CH [%]	80.0 (S)	80.0	80.0	80.0
DHW demand [%]	70.0 (S)	70.0	70.0	70.0
Heat pump power [GW]	0.0 (N)	0.0	0.0	0.0
Ground source heat pumps [%]	100.0 (S)	0.0	0.0	0.0
Air source heat pumps [%]	0.0 (N)	0.0	0.0	0.0
CH temperature [°C]	45.0 (S)	45.0	45.0	45.0
DHW temperature [°C]	55.0 (S)	55.0	55.0	55.0
Demand elasticity [-]	none	none	none	none
Electrolyzers [GW]	0.0 (N)	0.0	0.0	0.0
Nitrogen plants, refineries, etc. [TWh]	57.0 (S)	57.0	57.0	57.0
Sea shipping [TWh]	50.0 (S)	50.0	50.0	50.0
Aviation [TWh]	30.0 (S)	30.0	30.0	30.0
Metallurgy and steel production [TWh]	30.0 (S)	30.0	30.0	30.0
Fuel for the military [TWh]	5.0 (S)	5.0	5.0	5.0
Cement [TWh]	12.0 (S)	12.0	12.0	12.0
Other [TWh]	10.0 (S)	10.0	10.0	10.0

N - no data available or not included
S - simulator recommendations
R - data from a report or a reliable website

The "PV-based" scenario assumes that photovoltaics constitute the dominant renewable technology, with wind power removed from the analysed renewable generation mix. This configuration was selected to isolate the system-level effects of large-scale solar deployment, including its strong diurnal and seasonal variability. The scenario also incorporates planned pumped-storage power plants, resulting in increased energy storage capacity. The inclusion of additional storage is necessary to realistically assess the ability of photovoltaic generation to meet demand during periods of low solar availability and to mitigate surplus production during peak generation hours. The installed photovoltaic capacity in this scenario was estimated using the capacity factor approach, assuming a value of 12%. Based on the target annual electricity production of approximately 425000 GWh, the required installed capacity was calculated as:

$$\boldsymbol{P_{PV} = \frac{425000\ GWh}{8760\ h{\cdot}0.12} \approx 404\ GW} \quad (2)$$

The “Wind-based” scenario assumes that wind power constitutes the dominant renewable technology, with photovoltaic installations excluded from the analysed renewable generation mix. This scenario enables an independent evaluation of wind energy as the dominant renewable source, particularly in terms of its seasonal production patterns and variability driven by meteorological conditions. As in the PV-based scenario, planned pumped-storage power plants are included to reflect realistic future system flexibility and to examine the extent to which storage can compensate for fluctuations in wind generation. As in the other scenarios, dispatchable methane-based sources remain available to cover residual deficits and maintain uninterrupted supply. The installed wind capacity in this scenario was estimated using the capacity factor approach, assuming a value of 30%. Based on the target annual electricity production of approximately 425000 GWh, the required installed capacity was calculated as:

$$P_{Wind} = \frac{425000\ GWh}{8760\ h \cdot 0.30} \approx 162\ GW \tag{3}$$

The “PV + wind-based” scenario combines both photovoltaic and wind power generation, reflecting a diversified renewable energy portfolio with a significantly expanded installed capacity of both technologies compared to the current state. This scenario was selected to assess the complementarity of solar and wind resources, as their production profiles differ in both temporal and seasonal dimensions. Increasing the installed capacity of both sources allows for the evaluation of a system with a high penetration of variable renewable energy, representing a more advanced stage of the energy transition. The simultaneous inclusion and scaling-up of both technologies reduces the overall variability of renewable energy output and improves system stability compared to single-source scenarios. Planned pumped-storage power plants are again incorporated to evaluate their role in balancing residual mismatches between supply and demand under conditions of increased renewable generation. The installed capacities of photovoltaic and wind power in this scenario were estimated using the capacity factor approach, assuming values of 12% for photovoltaics and 30% for wind energy. The total annual electricity demand (approximately 425000 GWh) was equally distributed between both technologies to reflect a balanced generation mix. Accordingly, the required installed capacities were calculated as:

$$P_{PV} = \frac{212500\ GWh}{8760\ h \cdot 0.12} \approx 202\ GW \tag{4}$$

$$P_{Wind} = \frac{212500\ GWh}{8760\ h \cdot 0.30} \approx 81\ GW \tag{5}$$

The choice of these three scenarios was driven by the need to systematically isolate and compare the contributions of the two most readily available renewable energy sources in Poland solar and wind power both individually and in combination. This structured approach enables a clear assessment of their respective limitations, synergies, and storage requirements, while avoiding unnecessary complexity or speculative assumptions related to less mature technologies. As a result, the scenario set provides a coherent framework for evaluating potential development pathways for a renewable-based Polish energy system.

5. Results

The annual balance presented in Figure 3 confirms that the current configuration of the Polish energy system remains structurally dependent on dispatchable generation sources. Although renewable energy contributes a growing share of total production, annual renewable output does not fully align with total system demand when heating, transport, and industrial sectors are considered.

The annual methane requirement calculated in this scenario reflects the necessity of maintaining firm capacity to secure supply during periods of renewable underperformance. Even if annual renewable production approaches total annual demand, temporal mismatches between production and consumption result in residual deficits that must be covered by gas-fired generation.

This demonstrates a fundamental property of weather-dependent systems: annual energy neutrality does not imply hourly adequacy. The annual perspective alone therefore underestimates system balancing requirements.

Figure 4 shows that increasing photovoltaic capacity significantly raises annual renewable generation. However, despite high total yearly output, strong seasonal asymmetry persists. PV generation peaks during late spring and summer, while winter output remains insufficient relative to demand, especially when heating loads are electrified.

As a consequence, even with expanded pumped-storage capacity, the system requires substantial methane-based backup on an annual basis. The annual balance may appear favourable in terms of total renewable generation, but the structural winter deficit increases the need for dispatchable sources.

This finding highlights the limitation of solar-dominated systems in temperate climates with high seasonal heating demand.

In contrast, Fig. 5 indicates that wind-based generation provides a more favourable annual distribution relative to demand. Wind production in Poland is generally higher in autumn and winter, which better coincides with seasonal load patterns.

The annual methane requirement decreases compared to the PV-based scenario, suggesting improved structural compatibility between wind generation and demand. However, variability on shorter time scales still generates balancing needs that cannot be eliminated through annual energy surplus alone.

This confirms that wind energy is structurally better aligned with Poland’s demand profile than photovoltaics, though not sufficient as a single dominant source.

The combined scenario (Fig. 6) demonstrates the most balanced annual performance. The simultaneous expansion of both technologies reduces overall seasonal asymmetry due to partial complementarity between solar and wind generation.

Total renewable production increases as a result of expanded installed capacities, leading to a further reduction in methane demand. However, the results show that even a diversified and expanded renewable portfolio does not fully eliminate the need for dispatchable capacity.

The annual analysis therefore suggests that diversification significantly improves system adequacy but does not substitute the need for flexibility resources.

The hourly simulations under real 2023 weather conditions for the "Current state" scenario (Fig. 7) indicate that the existing Polish energy system remains structurally dependent on dispatchable generation throughout the year. As illustrated in Fig. 7, renewable generation only partially covers demand, and visible deficit periods occur during hours of low resource availability.

In April (Fig. 7), moderate contributions from both photovoltaic and wind generation are observed. Midday solar peaks partially reduce the residual load; however, evening hours remain strongly dependent on gas-fired generation. Wind output provides intermittent support but does not fully stabilise the system due to its variability.

In July (Fig. 7), the "Current state" scenario exhibits significant daytime photovoltaic surpluses, in some periods clearly exceeding demand. Owing to limited storage capacity, a portion of this excess generation cannot be effectively utilised. Evening demand continues to exceed renewable production, illustrating the persistent need for dispatchable backup.

In October (Fig. 7), reduced solar irradiation combined with variable wind output leads to more frequent deficit periods. As visible in the figure, demand exceeds renewable generation during extended intervals, particularly in the evening hours.

January (Fig. 7) represents the most critical month. Low solar availability and elevated heating demand coincide with variable wind conditions, resulting in prolonged deficit periods and sustained methane consumption. These results confirm the structural vulnerability of the current system configuration during winter conditions.

The "PV-based" scenario (Fig. 8), which excludes wind generation and relies exclusively on expanded photovoltaic capacity, demonstrates pronounced seasonal and diurnal variability.

In April (Fig. 8), high midday generation peaks frequently exceed instantaneous demand, in some cases by a significant margin. However, nighttime deficits persist, requiring continuous support from dispatchable sources.

In July (Fig. 8), substantial overproduction occurs during daylight hours. As clearly illustrated in the figure, generation exceeds demand for extended periods, leading to frequent curtailment due to limited storage capacity. Despite high annual photovoltaic output, evening and nighttime adequacy remains dependent on methane-based generation.

In October (Fig. 8), declining solar irradiation reduces midday output and increases both the frequency and magnitude of deficits during non-daylight hours.

January (Fig. 8) represents the least favourable period. Photovoltaic production is minimal, and demand exceeds generation almost continuously, meaning that nearly the entire load must be satisfied by dispatchable sources.

The "Wind-based" scenario (Fig. 9), in which photovoltaic installations are excluded and wind capacity is expanded, presents improved seasonal alignment with demand patterns.

In April (Fig. 9), the "Wind-based" scenario frequently achieves higher coverage of demand compared to the "PV-based" scenario, with several periods where generation approaches demand. Nevertheless, short-term wind variability continues to generate deficit hours.

In July (Fig. 9), the "Wind-based" scenario avoids the extreme midday surpluses characteristic of the "PV-based" scenario. Renewable production is more evenly distributed throughout the day, reducing both curtailment and variability.

In October (Fig. 9), relatively strong autumn wind conditions coincide with increased demand, resulting in fewer and shorter deficit events compared to the "PV-based" scenario.

In January (Fig. 9), the "Wind-based" scenario performs substantially better than the "PV-based" scenario. Wind generation covers a significant share of demand during many periods; however, extended low-wind intervals still lead to deficits requiring dispatchable support.

The "PV + wind-based" scenario (Fig. 10), which combines expanded photovoltaic and wind capacities, demonstrates the most stable operational behaviour among all analysed configurations.

In April (Fig. 10), reduced net-load volatility is observed due to the complementarity between solar and wind generation. Periods of surplus and deficit are less pronounced compared to single-technology scenarios.

In July (Fig. 10), surpluses remain present during sunny periods; however, the presence of wind generation reduces the intensity of overproduction compared to the "PV-based" scenario, as illustrated by lower peaks relative to demand.

In October (Fig. 10), wind contributions during periods of reduced solar irradiation significantly lower the frequency and duration of deficit events compared to both the "PV-based" and "Wind-based" scenarios.

In January (Fig. 10), the "PV + wind-based" scenario provides the highest renewable coverage among all analysed cases. Although deficits still occur, they are visibly reduced in both duration and magnitude compared to Fig. 8 and Fig. 9.

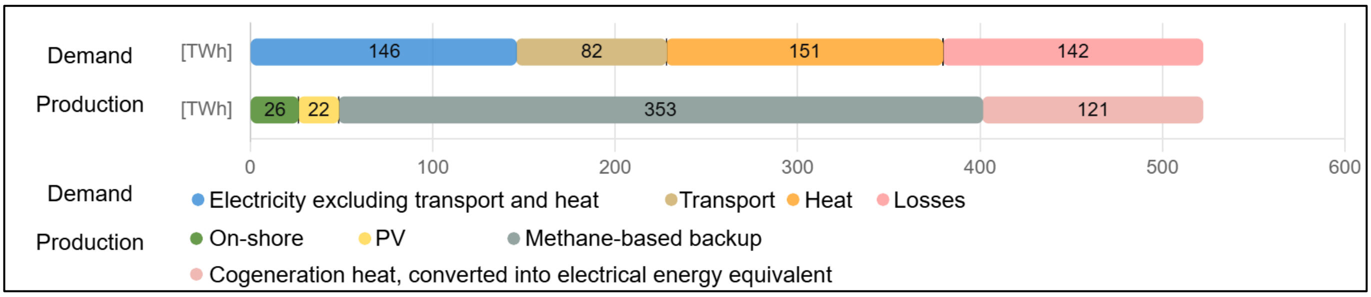

Fig. 3. Annual demand and production (scenario: current state)

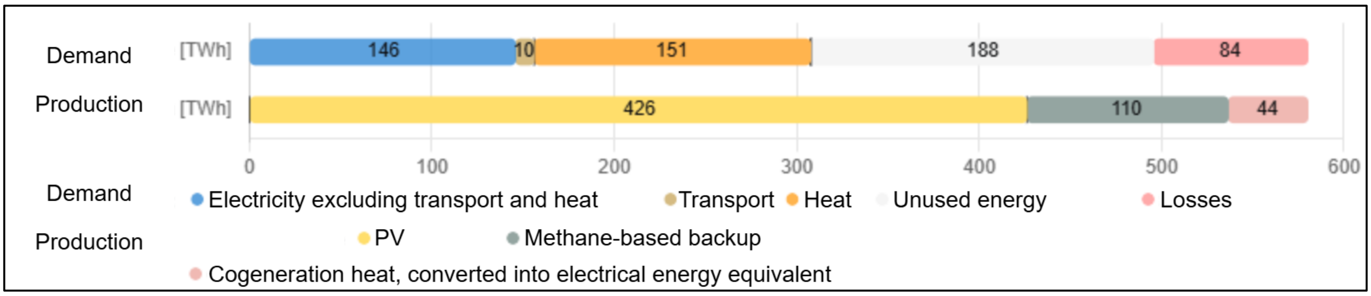

Fig. 4. Annual demand and production (scenario: PV-based)

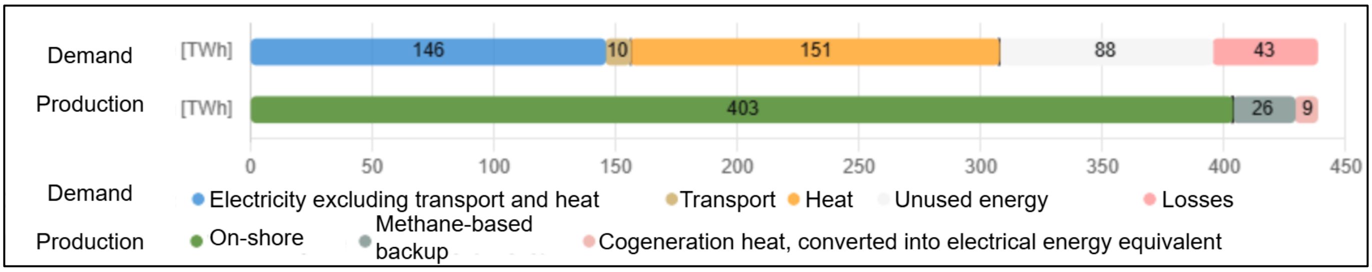

Fig. 5. Annual demand and production (scenario: wind-based)

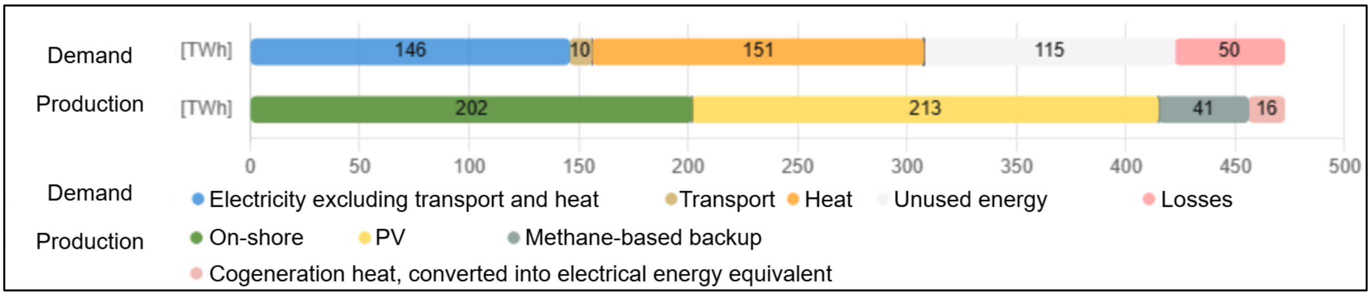

Fig. 6. Annual demand and production (scenario: PV + wind-based)

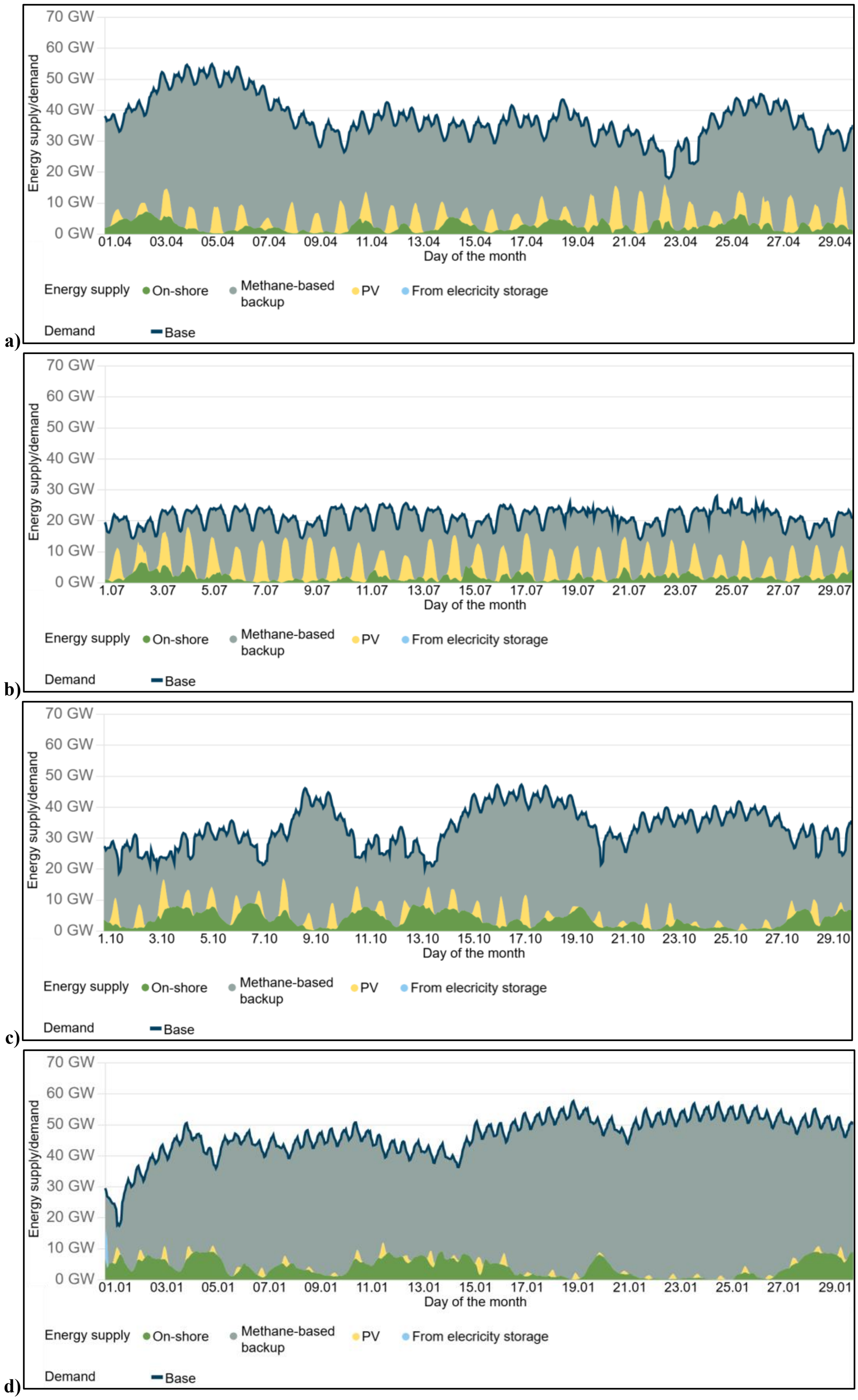

Fig. 7. Energy production and demand under 2023 weather conditions (scenario: current state): a) April, b) July, c) October, d) January

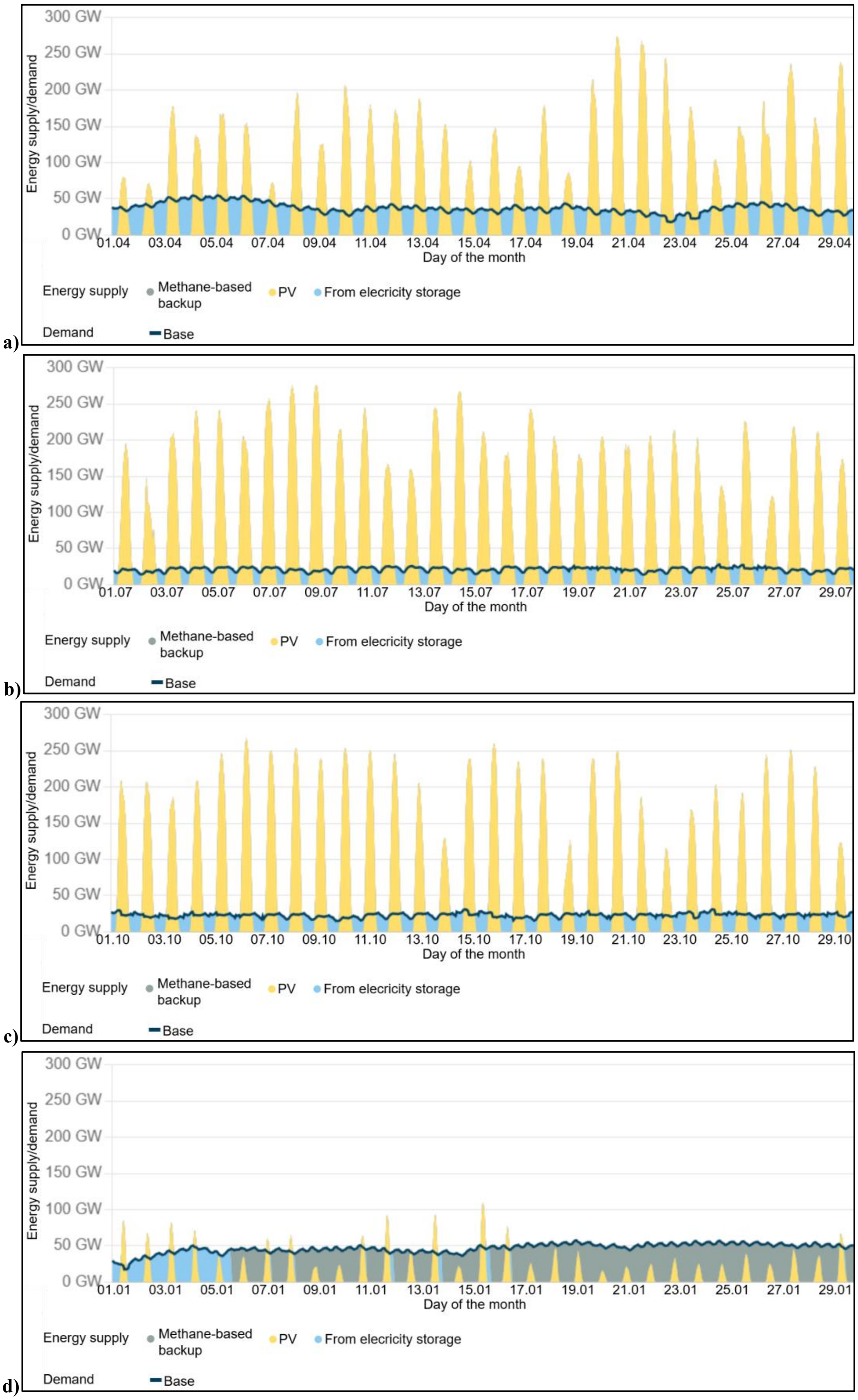

Fig. 8. Energy production and demand under 2023 weather conditions (scenario: PV-based): a) April, b) July, c) October, d) January

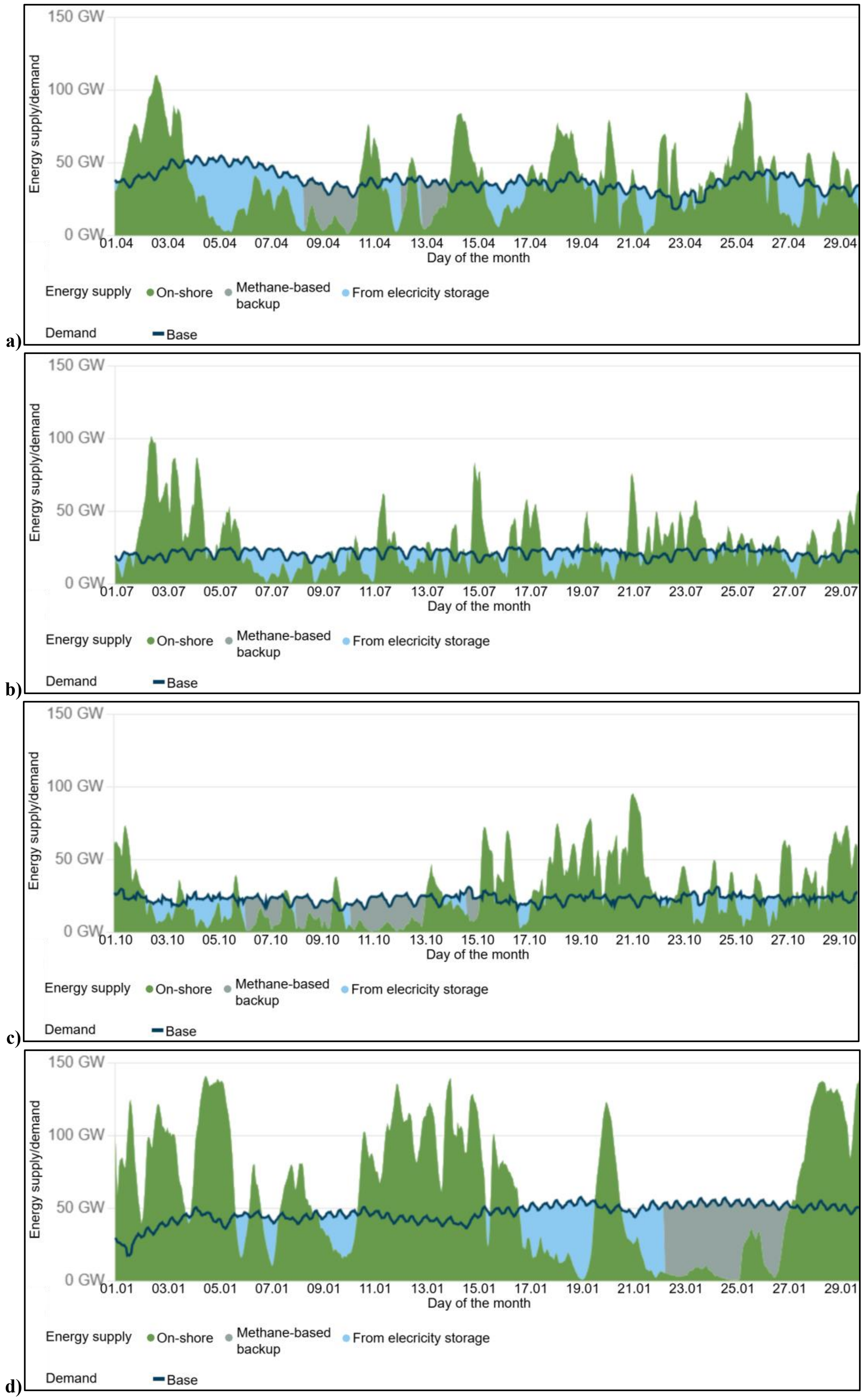

Fig. 9. Energy production and demand under 2023 weather conditions (scenario: wind-based): a) April, b) July, c) October, d) January

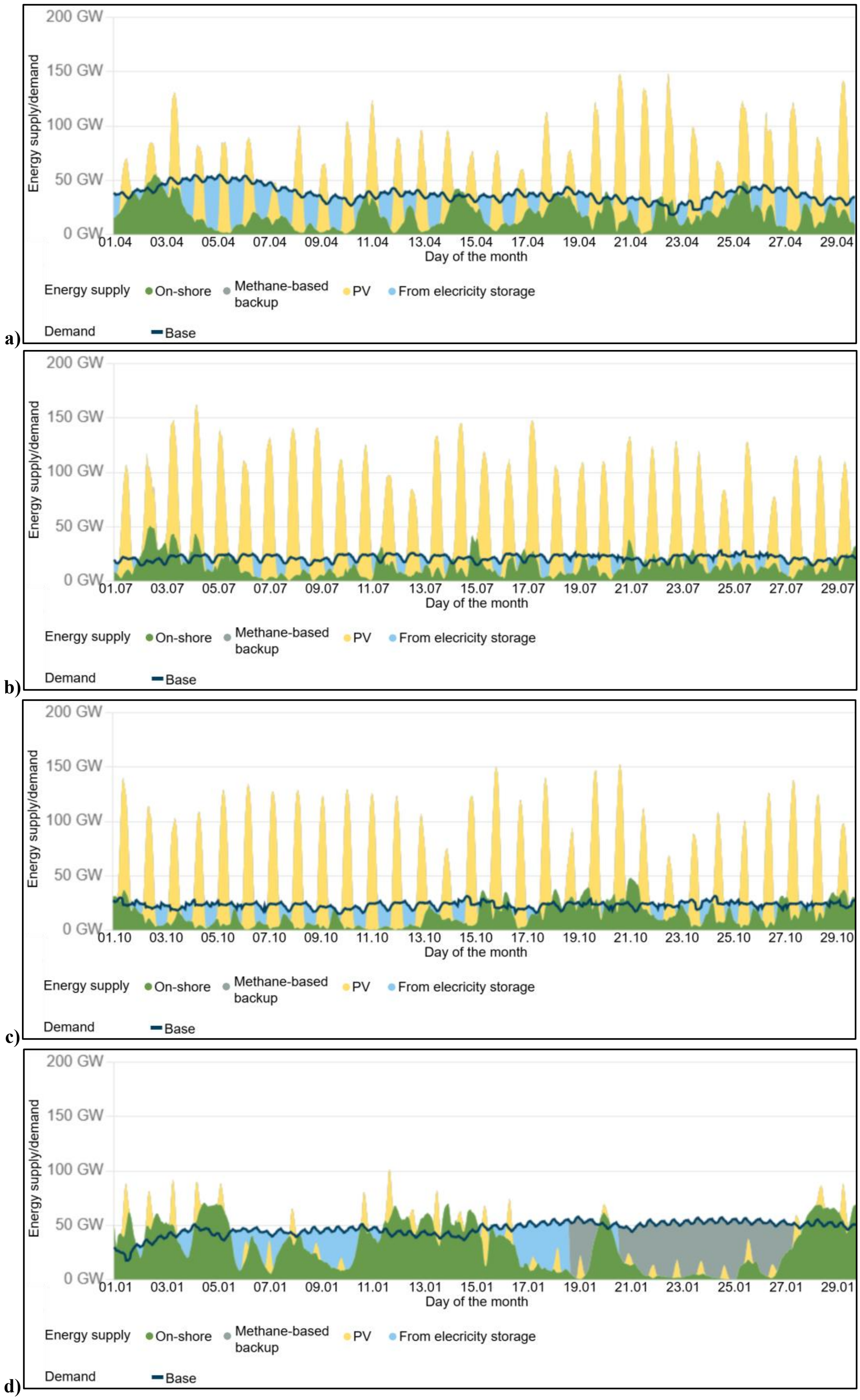

Fig. 10. Energy production and demand under 2023 weather conditions (scenario: scenario: PV + wind-based): a) April, b) July, c) October, d) January

6. Discussion

The results should be interpreted primarily as a comparative operational assessment of different RES configurations under Polish climatic and demand conditions. The study does not provide a full economic optimisation or detailed grid-expansion design; instead, it identifies relative system-level strengths and limitations of the analysed pathways. A major limitation of the present analysis is that the adopted simulation framework does not reproduce detailed nodal transmission constraints or congestion on specific network corridors. Consequently, the analysed scenarios should not be interpreted as evidence that high RES shares can be achieved without substantial grid reinforcement. In the Polish context, the large-scale expansion of photovoltaic and wind generation would require significant investments in both transmission and distribution infrastructure, including increased interregional transfer capacity, modernization of substations, and improved connection capabilities for new RES installations. These requirements would differ across scenarios, with RES-dominated pathways likely imposing higher balancing and network integration needs. Therefore, the results should be understood primarily as a comparative operational assessment, while the costs and engineering challenges of the required network expansion remain an important subject for further research.

The results confirm that the "Current state" scenario remains structurally dependent on dispatchable sources throughout the year. Although renewable generation already contributes meaningfully to annual electricity production, its variability—particularly during winter months—necessitates sustained support from gas-fired units. January emerges as the most critical period due to the coincidence of low solar irradiation, variable wind conditions, and elevated heating demand. This indicates that, under present infrastructure conditions, the Polish power system lacks sufficient flexibility and storage capacity to ensure full adequacy based solely on existing RES levels.

The "PV-based" scenario, characterised by expanded photovoltaic capacity and the exclusion of wind generation, demonstrates substantial annual production potential but suffers from pronounced diurnal and seasonal mismatches. While summer months exhibit significant midday surpluses, winter production remains critically low. The results show frequent curtailment events during high-irradiance periods and persistent nighttime deficits throughout the year. In winter, nearly the entire demand must be covered by dispatchable sources. These findings indicate that a solar-dominated system in Poland would require either massive long-term storage deployment or extensive dispatchable backup capacity, thereby limiting its structural feasibility as a standalone pathway.

In contrast, the "Wind-based" scenario exhibits improved seasonal alignment with demand. Wind resources in Poland tend to be stronger during autumn and winter months, partially compensating for increased consumption. Compared to the "PV-based" scenario, the wind-dominated configuration reduces winter deficits and lowers methane consumption. Additionally, the more even intraday distribution of wind generation decreases curtailment relative to solar-only expansion. However, prolonged low-wind periods still create adequacy risks, demonstrating that wind energy alone cannot guarantee uninterrupted supply without complementary flexibility mechanisms.

The most favourable operational performance is observed in the "PV + wind-based" scenario, which combines expanded photovoltaic and wind capacities. This configuration benefits from temporal complementarity between solar and wind generation, reducing net-load volatility across seasons. Summer surpluses are moderated relative to the "PV-based" scenario, while winter deficits are mitigated compared to both single-technology scenarios. Although residual shortages persist during extended low-resource events, their magnitude and duration are significantly reduced. Consequently, methane demand decreases relative to the other analysed configurations. The results demonstrate that diversification of renewable sources enhances system stability and reduces reliance on dispatchable generation.

Across all scenarios, storage systems play an essential but limited role. Pumped-storage facilities and other storage technologies primarily smooth short-term imbalances rather than eliminate structural seasonal deficits. The findings suggest that while storage expansion improves system flexibility, it cannot fully substitute for diversified generation portfolios under current technological and capacity constraints. In this context, the storage values adopted in the simulations should be understood as scenario assumptions within the simulator framework, rather than as optimised implementation values assigned to a single explicitly defined storage technology. Their role in the present study is to test the extent to which additional flexibility can reduce short-term imbalances in systems with high shares of variable renewable generation.

7. Opportunities and threats for RES Development in Poland

The RES development in Poland is accompanied by both significant opportunities and potential threats. Rising public environmental awareness and increasing demand for clean energy create favourable conditions for RES deployment. Initiatives and campaigns by local organizations that highlight air pollution issues can enhance public acceptance of RES projects. Advances in technology, including next-generation solar panels and energy storage systems, can improve the efficiency and economic RES viability investments, thereby promoting their adoption. Additionally, emerging funding mechanisms and active support from local governments play a critical role in facilitating RES development. Alignment of Poland's energy objectives with broader European decarbonisation strategies further presents opportunities to access financial resources and advanced technologies that can accelerate the country's energy transition.

Conversely, several threats may impede the RES development in Poland. The absence of clear legal frameworks and ambiguities in existing legislation can create uncertainty and hinder new investments. Inadequate energy infrastructure, including outdated transmission networks, may result in overloading and limit the integration of new generation sources. Furthermore, constrained interregional transmission capacity poses a significant barrier to RES expansion. The variability and intermittency of energy production, particularly from photovoltaic installations and wind farms, can impact electricity prices and market stability, discouraging potential investors. High capital costs for constructing wind and solar facilities, coupled with the need for investment in energy storage technologies, also constitute major constraints. Additionally, environmental and social considerations, such as impacts on local ecosystems or community opposition to new projects, must be addressed. Overall, while Poland possesses substantial potential for RES development, overcoming these challenges is essential to achieving the country's energy transition and decarbonisation objectives. These barriers are particularly relevant to the interpretation of the simulation results presented in this paper, because large-scale integration of photovoltaic and wind generation in Poland would require not only additional storage and dispatchable balancing resources, but also substantial reinforcement and modernisation of transmission and distribution infrastructure.

8. Summary and conclusion

This study assessed the current condition and prospective development pathways of RES in Poland using hourly simulations based on real weather data from 2015-2023 and actual electricity demand from 2023. Four scenarios were analysed: the "Current state" scenario, the "PV-based" scenario, the "Wind-based" scenario, and the "PV + wind-based" scenario. The objective was to evaluate system adequacy, variability, storage requirements, and dependence on dispatchable methane-based generation under different renewable configurations.

From a strategic perspective, the analysis indicates that Poland's renewable transition should prioritise balanced expansion of both wind and photovoltaic capacity rather than exclusive development of a single technology. Complementarity between these sources reduces variability and improves adequacy without disproportionately increasing curtailment. Furthermore, maintaining a certain level of dispatchable capacity remains necessary to secure reliability during prolonged low-renewable periods, particularly in winter.

The study also highlights the importance of demand-side flexibility, sector coupling, and hydrogen production in future system design. Although the simplified elasticity model does not capture full market dynamics, it illustrates the potential of demand response to partially mitigate supply–demand imbalances. Integration of electrolysers and thermal storage systems further enhances flexibility, especially in scenarios with higher renewable penetration.

An important limitation of this study is that the modelling framework does not account for system balancing costs or broader economic factors associated with integrating high shares of variable renewable energy. As a result, the findings should be interpreted primarily in terms of technical feasibility rather than economic optimality. The exclusion of cost-related aspects may influence the assessment of scenario realism, particularly with respect to large-scale overcapacity, storage deployment, and the utilisation of dispatchable backup sources.

In conclusion, the transformation of the Polish energy system toward high renewable penetration is technically feasible but requires a diversified generation mix, expanded storage infrastructure, and maintained dispatchable capacity during the transition phase. Among the analysed pathways, the combined "PV + wind-based" scenario provides the most balanced and resilient configuration under Polish climatic conditions. The results underline that system stability in a renewable-dominated framework depends not only on installed capacity but also on technological diversity, flexibility resources, and seasonal complementarity of energy sources.

Future research should focus on incorporating dynamic market mechanisms, more detailed storage modelling, cross-border electricity exchange, and long-term meteorological variability to further refine adequacy assessments and investment strategies. Future work should therefore integrate the present operational framework with detailed techno-economic modelling and higher-resolution power system constraints.

Acknowledgements

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Appendix

Table 4. Simulation parameters definitions

Parameter	Definition
Off-shore wind	Installed off-shore wind power capacity
On-shore wind	Installed on-shore wind power capacity
Photovoltaics	Installed photovoltaics power capacity
Atom power plant	Installed nuclear power capacity
Methane-based backup	Dispatchable gas-fired power plants installed capacity, calculated as the maximum hourly demand over the year, the third column allows editing of the operational efficiency of gas power plants
Thermal power plants operating in cogeneration percentage	Waste heat generated portion by gas-fired power plants is allocated for heating purposes through cogeneration in combined heat and power plants
Double-sided panels share in east-west orientation	Vertically mounted bifacial photovoltaic panels share oriented in the east–west direction, the remaining panels are oriented in accordance with current practice, approximately facing south at varying tilt angles
Modern turbines share	Modern wind turbines share with significantly improved performance parameters and a higher capacity factor compared to the older turbine models commonly installed in Poland prior to the introduction of the 10H regulation
Loss during transmission	Not all electricity injected into the grid by energy sources reaches end users, currently, transmission and distribution losses amount to approximately 5%; however, in the future, with the wider deployment of local energy sources and the grid infrastructure modernization, this value may be reduced
Gas power plants efficiency	Fuel energy converted into electricity in gas-fired power plants share: combined-cycle gas turbine (CCGT) units achieve efficiencies of up to 62%, while smaller open-cycle gas turbine (OCGT) units typically operate at efficiencies of around 40%
Stationary batteries	Stationary battery systems capacity, ranging from residential installations to large-scale energy storage facilities
Car batteries	Electric vehicle batteries capacity available for grid interaction. For example, if Poland had 10 million electric vehicles with an average battery capacity of 50 kWh, and 10% of this capacity were made available for grid storage purposes, approximately 50 GWh would be accessible
Pump storage power plants	Pumped storage power plants capacity
Large PTES	Large-scale pit thermal energy storage (PTES) systems capacity
Small domestic	Small-scale thermal energy storage systems capacity
Heat demand in industry	Industrial heat demand expressed as demand percentage under a fully electrified industrial sector
Heat demand in industry - heat storage, capacity	In a future energy system dominated by weather-dependent renewable sources, dynamic electricity tariffs are expected to operate, incentivising energy-intensive industries to consume electricity during low prices periods and store it for later use, including in the form of heat
Heat demand in industry - customers with storage facilities percentage	Some industrial facilities will be equipped with thermal energy storage systems, while others will not
Waste heat from industry percentage transferred to district heating networks	Waste heat from industrial processes may subsequently be utilised in district heating networks, where such infrastructure exists and where it is economically viable
Heat consumers connected to the network	Heat consumers share connected to district heating networks, assumed to make thermal energy storage use
Consumers with heat storage facilities, including the CH	Consumers share equipped with thermal energy storage systems, including both those connected to district heating networks and those operating independently with on-site storage, using electricity for heating via heat pumps and electric heaters or electrode boilers
Heat consumers - without heat storage facilities	Consumers share not connected to thermal energy storage systems, particularly households using heating technologies that do not allow for heat storage, such as air-to-air heat pumps, infrared heaters, or similar devices
Demand	Electricity consumption expressed as current consumption level percentage, a 100% value corresponds to hour-by-hour electricity consumption identical to that observed in Poland in 2023 (after excluding demand for heating purposes), a 85% value indicates a 15% reduction in electricity consumption relative to the baseline level
Road transport	Full one-to-one current road transport sector electrification (including passenger cars, trucks, and other vehicles) would require approximately 100 TWh per year, corresponding to 100% value, in a scenario where energy efficiency measures reduce demand by 20%, 80% value should be entered, an option to edit detailed input data is also available, allowing electricity demand to be estimated based on several key parameters
Base demand for CH	Full space heating electrification in existing buildings corresponds to 100% value, in a scenario where energy efficiency measures reduce heating demand by 20%, 80% value should be entered, an option to edit detailed input data is also available, allowing heating demand to be estimated based on several key parameters

DHW demand	Percentage value indicating the extent to which demand for heat used for domestic hot water (DHW) production is reduced. A 100% value represents no improvement in energy efficiency, while 70% indicates a reduction in demand to 70% of the current level
Heat pump power	Heat pump capacity is expressed in electrical power demand terms, while the corresponding thermal output is approximately four times higher
Ground source heat pumps	Ground-source heat pumps share, for which the ground serves as the lower heat source, owing to the nearly constant ground temperature, the heat pumps performance is largely ambient air temperature independent, although variations in efficiency related to changes in radiator operating temperatures, driven by fluctuations in space heating demand due to outdoor temperature changes, are taken into account, the ground-source heat pumps share is calculated as 100% minus the air-source heat pumps share
Air source heat pumps	Air-source heat pumps share, for which ambient air serves as the lower heat source; the heat pumps efficiency decreases with declining outdoor air temperature
CH temperature	Temperature to which water is heated in the heating system, when this temperature is high (e.g. hot radiators in an inefficient building with undersized heat emitters), heat pumps operate at lower efficiency than in systems with lower supply temperatures, such as well-insulated buildings equipped with large-area heat exchangers, including underfloor heating or ceiling capillary mats
DHW temperature	Temperature to which domestic hot water is heated at the use point of use. When this temperature is high, heat pumps operate at lower efficiency compared to systems with lower hot water temperature requirements. Lower temperatures are typically associated with energy-efficient buildings equipped with large-area heat exchange systems, such as underfloor heating or ceiling capillary mats
Demand elasticity	Demand-side management is a highly complex issue, the extent to which it can reduce energy consumption during supply shortages periods (and potentially increase consumption during surplus periods) depends on regulatory frameworks, energy market design, the dynamic tariffs implementation, and the consumers responses across different groups and sectors to price signals, these responses are influenced not only by current supply–demand conditions but also by factors such as the energy storage level, weather forecasts, and system expectations, in this study, a simplified and easily adjustable model is applied, using a single demand elasticity coefficient characteristic for each sector, when the demand elasticity coefficient is set at 10%, a situation in which electricity production equals 50% demand results in a 10% reduction in demand, conversely, when electricity demand equals 50% available supply, demand increases by 10%, if electricity production further decreases relative to demand by a factor of two (to 25% demand), consumption is reduced by an additional 10%, resulting in a total 20% reduction (to 80% demand level without price elasticity), similarly, when demand represents 25% supply, electricity consumption increases by 20%, it is assumed that beyond a supply-demand ratio 4:1, no further demand response occur, thus, with a demand elasticity coefficient 10%, demand variations are limited to ±20%
Electrolyzers	Electrification represents an attractive solution to many challenges across the economy; however, in certain sectors, the hydrogen or hydrogen-derived compounds use is more rational, both as an energy carrier and as a feedstock for chemical processes, this applies, for example, to oil refineries, nitrogen fertiliser plants, and the steel industry, where hydrogen can be used for the iron oxides reduction, in the model interface, the electrolyser capacity is specified along with the percentage hydrogen demand relative to a full hydrogen adoption scenario, referenced to 2023 conditions
Nitrogen plants, refineries, etc.	Currently, refineries and nitrogen fertiliser plants use fossil fuels as feedstocks for the plastics, ammonia, and subsequently nitrogen-based fertilisers production, in the future, hydrogen produced via electrolysis is expected to replace fossil feedstocks in these processes
Sea shipping	Deep-sea shipping is unlikely to be powered by batteries; instead, hydrogen-based fuels, such as ammonia, can be employed as energy carriers in this sector
Aviation	Long-distance flights require fuels with a significantly higher energy density, in this context, hydrogen or hydrogen-based synthetic fuels (e-fuels) can serve as viable energy carriers
Metallurgy and steel production	In metallurgy, it is necessary not only to provide high-temperature heat but also to reduce the ore, currently, coke is used for this purpose, whereas in the future, hydrogen is expected to serve as the reducing agent
Fuel for the military	Heavy military equipment (e.g., tanks) requires fuels with high energy density and the capability for rapid refueling in the field on the battlefield, high-power chargers refueling capable, for instance, an entire tanks battalion within 30 minutes, cannot be relied upon, currently, the most viable alternative to conventional fossil fuels in this context is hydrogen-based synthetic fuels (e-fuels)
Cement	Cement production requires fuels that provide high temperatures and substantial energy input, hydrogen could serve as a substitute for the coal currently used in this sector, while an alternative approach is the direct heat electrification
Other	Various smaller industrial sectors require high-temperature heat, typically supplied through the natural gas or gas-based chemical energy carriers combustion