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Supercapacitors as Key Enablers of Decarbonization and Renewable Energy Expansion in Poland

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Abstract: Decarbonization and the replacement of coal-fired power plants with solar and wind farms require adequately large energy storage facilities. This is especially important in countries such as Poland, which still do not have a nuclear power plant. Supercapacitors represent a new generation of energy storage. The paper demonstrates that the use of supercapacitors presents an opportunity to increase the share of solar and wind power plants in the energy market. Furthermore, there is no need to replace all coal plants (that are being gradually decommissioned) with nuclear ones. The paper underscores that any further decarbonization and increase in the share of renewable energy sources (RES) in the Polish energy market necessitates the deployment of large energy storage facilities. Rechargeable batteries have a short lifespan, and their production results in significant greenhouse gas emissions. The widespread use of supercapacitors in a new generation of energy storage unveils new possibilities and bolsters decarbonization efforts. Based on an annual analysis of hourly electricity production from wind farms and PVs, a formula is proposed to calculate the capacity of energy storage necessary for the operation of the grid-powered national electricity, mainly from RES.

Keywords: decarbonization; supercapacitors; energy transition; RES

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1. Introduction

Poland is on the cusp of an energy transformation, one that marks a significant shift away from coal-fired power generation. Notably, Poland stands out among its European counterparts due to the absence of nuclear power facilities, making its energy transition a unique endeavor. In recent years, the nation has seen the simultaneous growth of renewable energy sources and the gradual phasing out of coal mining and coal-based electricity generation. This transition is driven by the need to reduce carbon emissions, aligning with global efforts to combat climate change.

However, the complete substitution of coal-fired power plants with renewable sources presents a formidable challenge, particularly in a country the size of Poland. The enormity of this task necessitates substantial energy storage capacities, a feat that proves almost insurmountable within Poland's geographical constraints. The construction of numerous pumped-storage power plants, a common solution in regions with mountains, is impractical in Poland due to its predominantly flat terrain. Even in mountainous areas, the ecological and environmental impacts of such projects raise significant concerns.

To address this challenge, Poland took a decisive step on 15 December 2022, by signing a contract with Westinghouse Electric Company for the construction of its first nuclear power plant, set to commence operations after 2033. The plant will incorporate three Westinghouse AP1000 reactors, with an estimated construction cost of approximately USD 20 billion [1].

The successful decarbonization of Poland hinges primarily on the effective utilization of renewable energy sources. Yet, to harness the full potential of renewables, large-scale energy storage facilities are indispensable.

Today, Poland is planning to launch the first reactor with a capacity of 1–1.6 GW by 2033 and expand to six reactors with a total capacity of 6–9 GW by 2043 [2]. The forecasts predict that nuclear energy could account for up to 16% of the overall energy generation by 2040. At the same time, all steam coal mines in Poland will be closed (there are steam coal for power plants and coking coal for steelworks). At most, a few percent of the energy market will be generated in gas power plants. It means that about 80% of the electricity must be generated by RES—it is difficult to implement. From a practical perspective, it is not technically possible to have a high share of RES (about 80%) in the energy market unless large energy storage facilities are built. The power generated by wind farms and PVs is not constant and cannot be programmed like in a thermal power plant. PVs generate power only during the day. The operation of PVs and wind farms depends very much on the weather. The most unfavorable case occurs on cloudy and windless days then the RES produce less than 10% of their average power and it could last continuously for several days. It is a big problem for the national electricity grid. Energy storages allow not only to supply the power grid during the nights, but also during periods of cloudy and windless weather. Therefore, if RES are the dominant source of electricity for the power grid, an appropriately large energy storage facility is necessary. Without energy storage, it is not possible to use RES on a large scale in the national power grid.

Historically, rechargeable batteries, particularly lithium-ion batteries, have been a popular choice. However, their suitability for powering an entire country is debatable, given the significant greenhouse gas emissions associated with their production and their relatively short lifespan [3]. This is an important issue that is very often ignored in many considerations and discussions. The production of batteries involves significant greenhouse gas emissions. In the case of lithium-ion batteries, it is necessary to take into account not only the energy used directly to produce the battery in the factory, but also the energy necessary to extract lithium ores in the mine and to chemically and physically process these ores. The decommissioning of coal-fired power plants and coal mines will significantly reduce greenhouse gases emissions, but unfortunately, a thorough analysis of the carbon footprint may unexpectedly show that the use of large battery energy storage facilities (which are needed for RES) will not result in effective decarbonization. That issue is not as obvious and simple as it may seem at first glance [4].

In recent years, a compelling alternative to rechargeable batteries has emerged in the form of supercapacitors. These high-performance energy storage devices are changing the game, opening up new possibilities for large-scale energy storage. Unlike batteries, supercapacitors excel in stationary energy storage, making them an ideal match for proximity to solar or wind farms.

The journey toward decarbonization is both complex and long term. It extends beyond the shift from fossil fuels to renewable sources; the choice of energy storage technology is paramount in ensuring effective decarbonization. Detailed comparisons of decarbonization scenarios are available in associated papers [5].

The structure of this article is as follows:

- Energy landscape analysis: Examining the energy structure of Poland in relation to other EU countries, with a focus on the dominant role of hard coal and lignite.
- Coal quality parameters: Delving into the qualities of coal as an energy source and its anticipated decline due to emissions concerns.
- Sustainable development legislation: Analyzing legal acts related to sustainable development and their implications for Poland's energy transition.
- Nuclear and renewable energy: Assessing the current share of nuclear energy and renewable sources in Poland's energy market.
- Batteries vs. supercapacitors comparison: properties and most important differences.
- Renewable energy potential: Exploring the untapped potential of renewable energy sources within the country.
- Estimating the necessary capacity of energy storage to power the national power grid, assuming the use of only RES.

The article concludes by emphasizing that effective decarbonization requires not only the replacement of fossil fuels with renewables but also a thoughtful choice of energy storage solutions. In this critical juncture, supercapacitors stand out as a promising path forward, offering newfound possibilities for Poland's energy future.

2. Poland's Energy Mix

In the context of electrical energy production within the European Union, a core group of 12 member states collectively generate 88% of the total electricity. Figure 1 illustrates the energy production volumes of member states for the years 2012–2021.

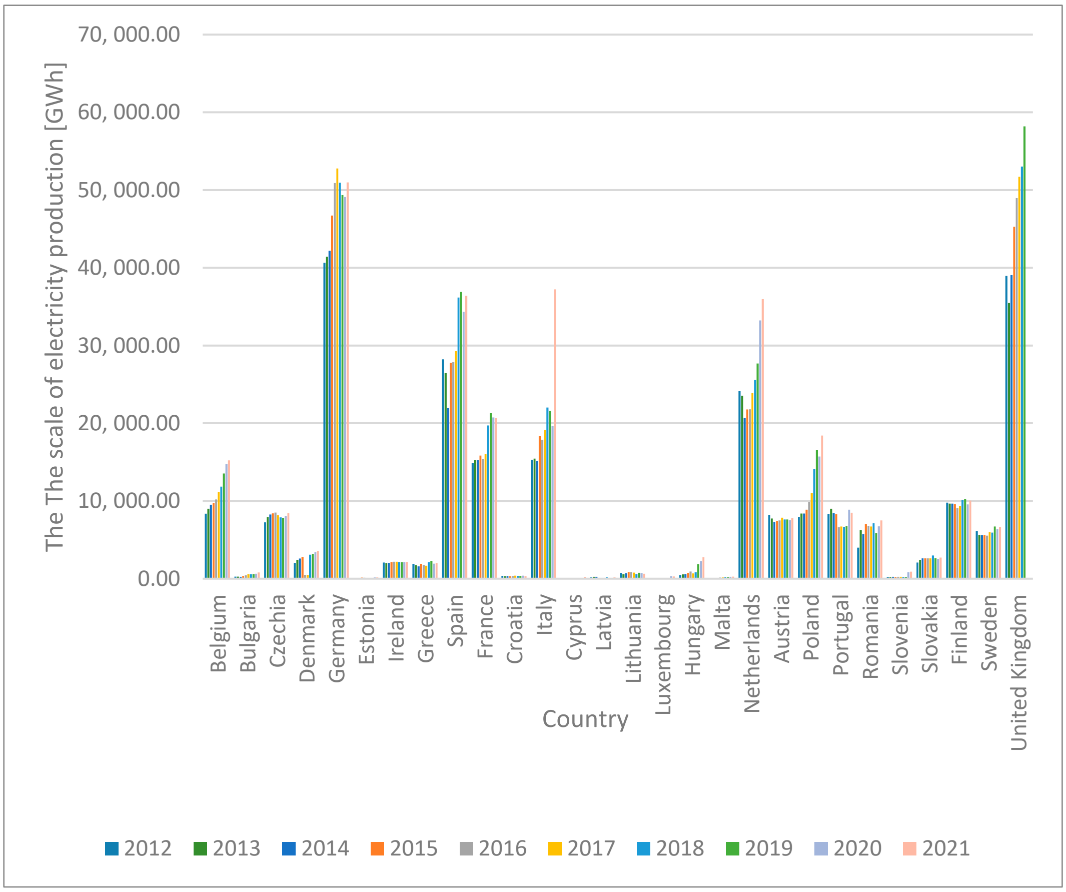


Figure 1. Electricity production volume in selected EU countries in 1990–2018, thousand GWh, source: own study based [6].

Germany, Italy, Spain, and Netherlands emerge as the leading electricity producers among the member states, jointly accounting for 57% of the total EU production. Following them are France and Poland, each producing approximately half the out-put of Germany. Collectively, these six countries are responsible for just over 71% of the total energy produced in the European Union. Belgium, and Finland are next, each contributing around 5% to the EU's total energy production.

The energy resource mix utilized for electricity production varies significantly among EU member states, as depicted in Figure 2. Meeting the energy policy goals of achieving a 20% share of renewable energy sources presents a challenge for many countries. Currently, Poland has the lowest utilization of renewable sources—below 10%—among the major energy producers in the EU. Other countries with renewable energy shares below 20% include France, the United Kingdom, the Netherlands, Belgium, and the Czech Republic. In the era of decarbonization, the countries with the highest levels of solid fuel usage, namely hard coal and lignite, are Poland, followed by the Czech Republic, Germany, the United Kingdom, the Netherlands, Italy, Spain, Finland, Austria, Belgium, France, and Sweden.

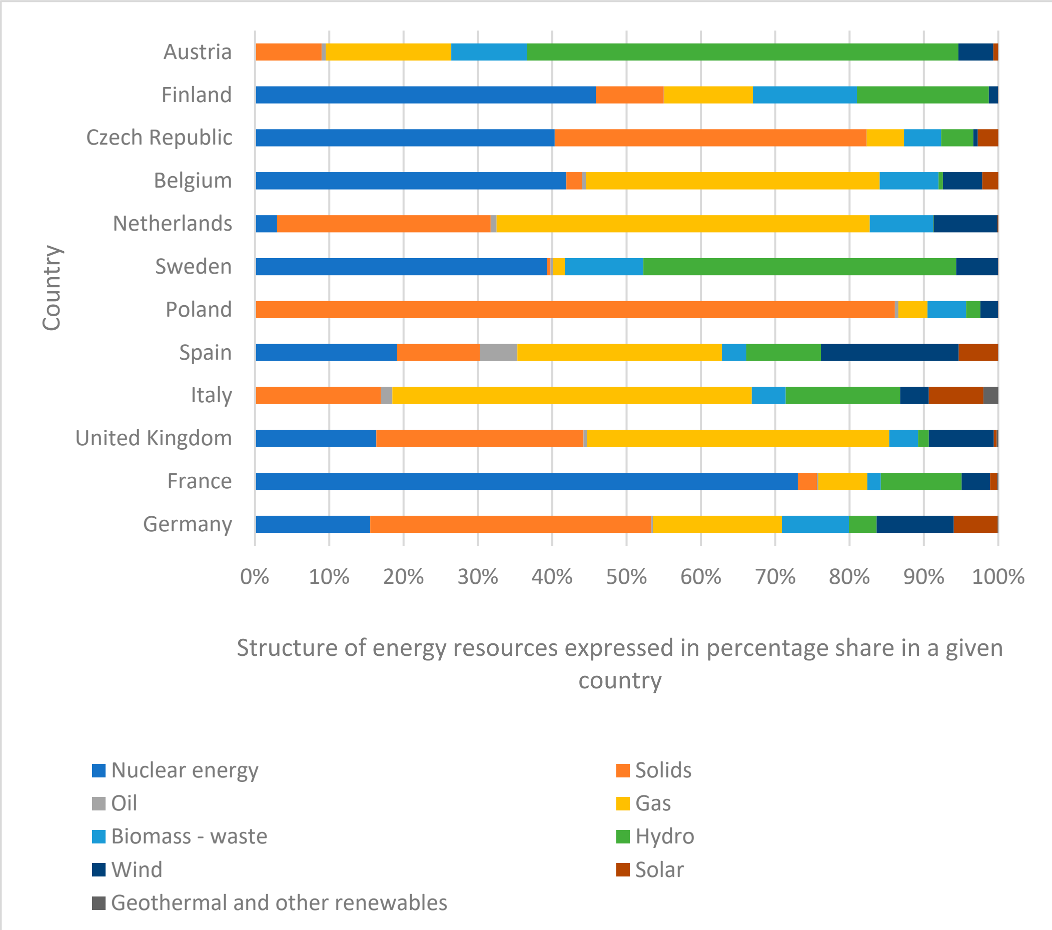


Figure 2. Structure of energy resources expressed in percentage share in a given country, source: own study based [7].

Fossil fuels continue to dominate the primary energy structure in Poland, accounting for approximately 89% of the overall energy supply in 2021. Coal, constituting the largest portion at 41.13%, remains the primary contributor, followed by crude oil at 29.93% and natural gas at 17.94%. Both hard coal and lignite play a significant role in Poland's energy sector and economy. In comparison to other member countries of the IEA, Poland had the highest proportion of coal usage in primary and secondary energy production, total energy supply, total final consumption, and electricity generation in 2020. Additionally, Poland held the second-largest share in heat production. The considerable reliance on coal positions Poland as the second-highest emitter of CO_2 per unit of energy supply among IEA member countries, and fourth-highest in terms of CO_2 emissions per unit of GDP. However, there has been a gradual decline in the significance of coal within Poland's energy system over the period from 2010 to 2020. This decline is evident in the reduced proportion of coal in the total energy supply, electricity generation, district heating, and total final consumption.

The process of decarbonization and the replacement of coal-fired power plants with cleaner energy sources are significantly impacting the domestic coal market in Poland. In 2022, the production of hard coal in Poland declined to 52,832 thousand tonnes (Mg), representing a decrease of 3.9% compared to the previous year. The total stock of hard coal in mines by the end of December 2022 amounted to 1794 thousand tonnes (Mg), reflecting a decrease of 121 thousand tonnes (Mg) compared to the end of 2021. Total hard coal sales in 2022 reached 40,021 thousand tonnes (Mg), indicating a decrease of 4908 thousand tonnes (Mg) from 2021. During this period, sales in the domestic market decreased by 1094.8 thousand tonnes (Mg), corresponding to an 11% decrease.

Notably, sales to commercial and non-professional heating plants increased by 6%, and sales to other industrial customers saw a 13% rise. Conversely, sales to coking plants decreased by 1%, sales to the commercial power industry reduced by 11%, sales to the industrial power industry decreased by 25%, and sales to other domestic customers dropped by 17%. The export of high-quality coal in 2022 reached 2,877,000 Mg, while coal imports to Poland amounted to 16,722,231 Mg. A significant portion of these imports originated from South Africa, accounting for 3,576,400 Mg. Another concerning trend in the mining sector was the growing demand for coal from the energy sector, which was met with imported coal.

Several factors contributed to the decline in raw material sales, including milder winters, increased electricity production from wind turbines, and electricity pricing policies. However, 2022 witnessed a notable surge in coal demand, leading to a resurgence in the share of electricity production from coal, which returned to 80% of the total production [8].

With regard to 2022, in 2021 [8,9], the following will occur (Figure 3):

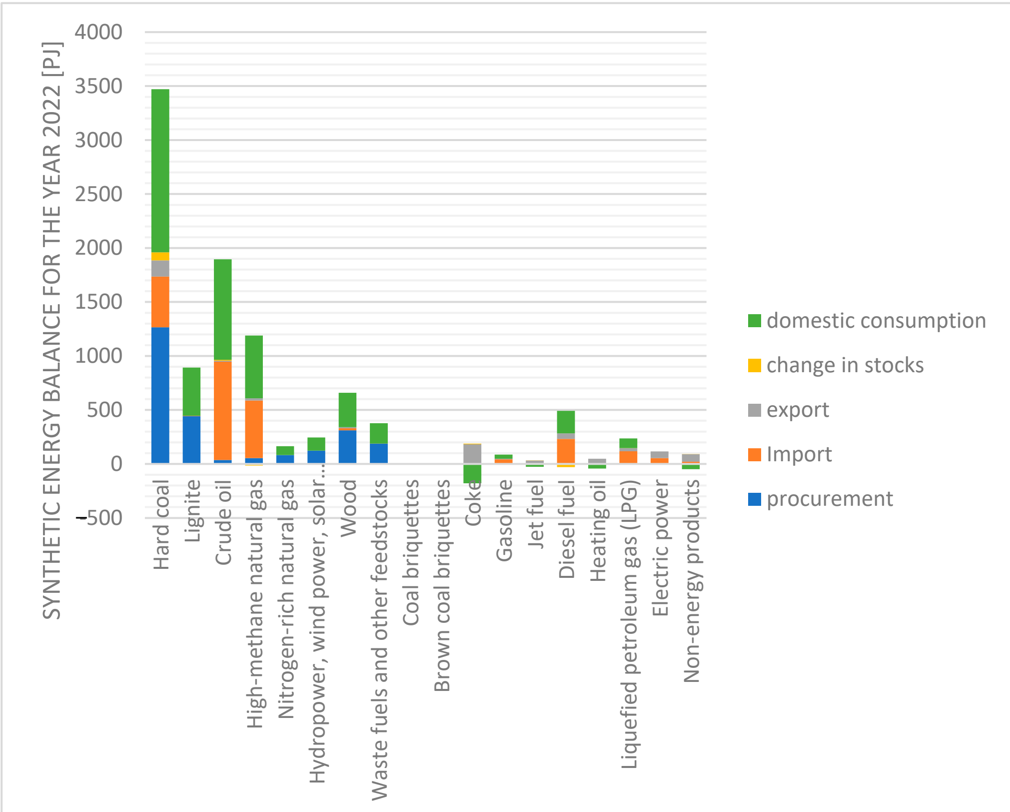


Figure 3. Structure of primary energy consumption, source: own study based [6].

- Fossil fuels cover 85% of final energy consumption in Poland.
- A total of 45% of final energy comes from coal, of which 36% from hard coal and 9% from lignite.
- A total of 10% of energy was consumed from renewable sources, of which 8% from biomass (wood).
- A total of 2% of energy needs were covered in total by hydropower, photovoltaics, wind, geothermal and ambient energy.
- During the decade, the share of coal decreased by 8% and oil by 2%, while the share of natural gas increased by 3% and renewable energy by 6%.

Electricity production in 2020 was as follows:

- A total of 72.4% is the share of coal in electricity production, which is 2.7% more than in the previous year.
- Production from hard coal reached the highest level in 10 years—84 TWh and an increase of 1.4%.
- Production of energy from natural gas decreased by 0.7 TWh, which translated into a decrease in the share of gas by 1.6%.
- Production of energy from photovoltaics doubled compared to 2020 and amounted to 3.8 TWh.
- Energy production from all renewable energy sources (RES) sources last year amounted to 30 TWh, which is a record result. Despite this, the share of RES in the production mix fell to 16.7% from 17.7% recorded in 2020.

Poland's energy policy is changing, and the country has achieved significant successes in the field of energy transformation (Figure 4). In recent years, government support for photovoltaics (PV) has made Poland one of the most growing renewable energy markets in the EU. Over the five years from 2016 to 2021, photovoltaic capacity in Poland increased from just 0.2 gigawatts (GW) to 7.7 GW in 2021, mainly due to the use of small, distributed photovoltaic systems in residential buildings (5.9 GW). The country also has a well-developed and comprehensive offshore wind strategy, with contracts for 5.9 GW by 2027 and plans for at least 11 GW by 2040.

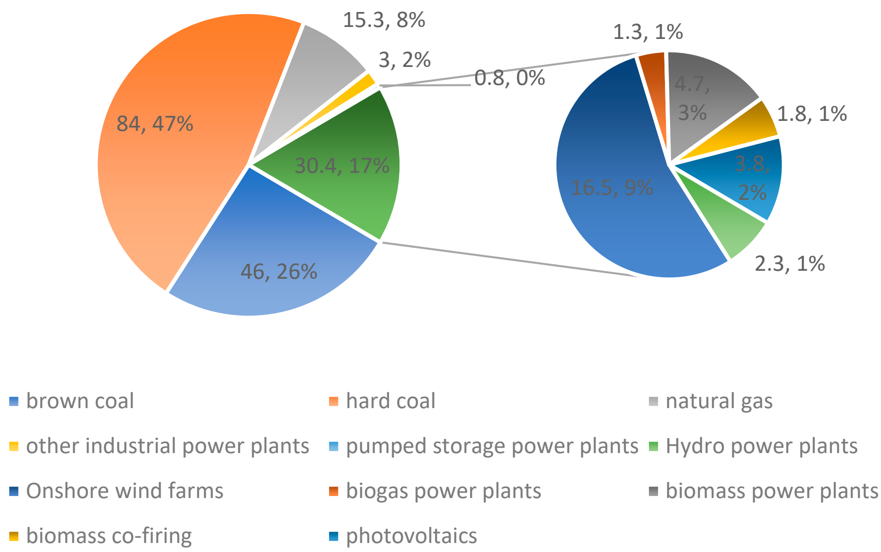


Figure 4. Electricity production in 2021, source: own study based on [10].

The change in electricity production from renewable sources in the last decade is as follows [10]:

- In 2021, 30.4 TWh of electricity was produced from RES, which is 8.5% more than in 2020.
- Wind energy accounted for more than half (54%) of production from renewable sources, while the share of biomass is 15% and photovoltaics 13%.
- Within 10 years, the supply from RES increased by 80%—from 16.8 TWh in 2012 to 30.4 TWh in 2021.
- Apart from photovoltaics, the largest increase in production was recorded in wind farms (+250% in a decade).

All changes are shown in Figure 5.

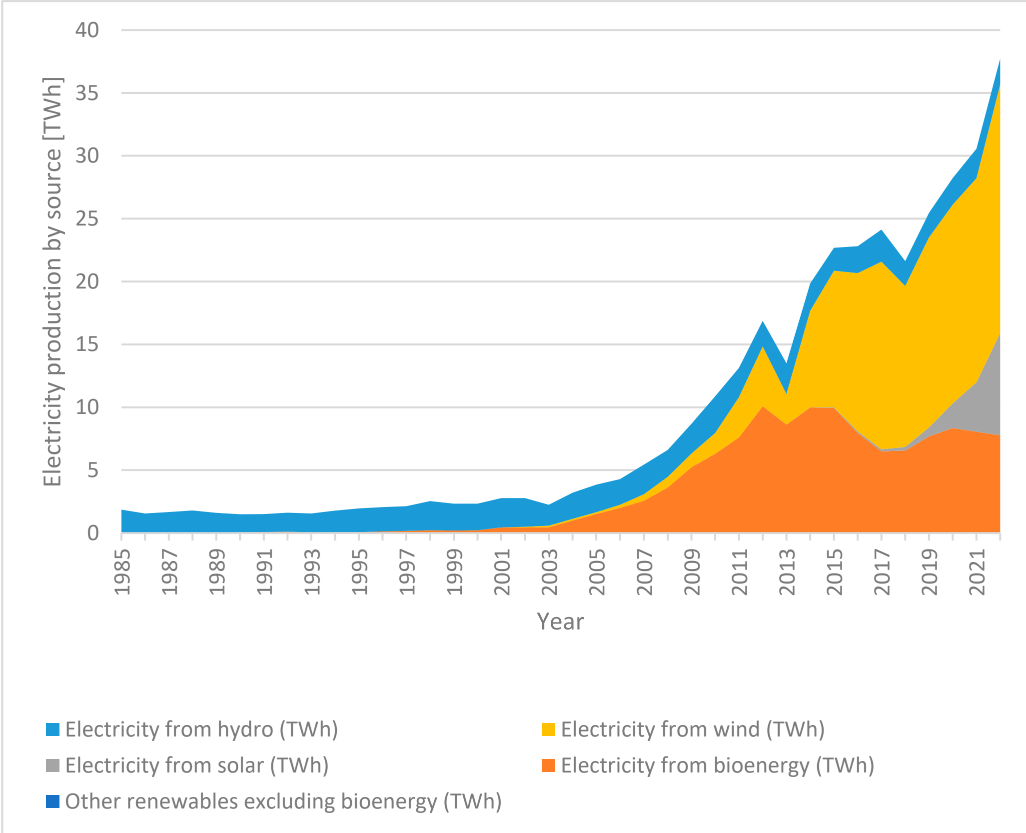


Figure 5. Change in electricity production from renewable sources, source: own study based on [11].

Analyzing the growth of electricity production from renewable sources, a theoretical model of this energy production from renewables has been developed with a perspective to 2040. This model takes into account the challenges associated with forecasting this consumption in various contexts and scales, from individual enterprises to entire regions and countries. The text [12] presents different methods of forecasting electricity consumption, including models of artificial neural networks, and the authors have conducted a comparative analysis of forecasting methods for electricity consumption, considering the main advantages and disadvantages, the scope of application, and the specific features of operational models. The authors emphasize the need for additional research and development of forecasting methods that can take into account the specificity of each task of forecasting electricity consumption.

Building a prognostic model with a perspective of several decades requires the adoption of assumptions that are burdened with uncertainty. This is mainly due to the variability of legal regulations, economic factors (fossil fuel prices, tax rates, GDP), and the contribution of innovation to technology development, especially energy intensity (or energy efficiency). An unexpected technological leap in one of the alternative reduction technologies could significantly increase its economic attractiveness compared to the others. Each of these sources of uncertainty affects the credibility of the developed model. Due to the presented uncertainties, deep learning techniques were used to forecast individual energy carriers, and LSTM (long short-term memory) networks are particularly useful for forecasting electricity from renewable energy sources (RES) for the following reasons:

- Ability to process data sequences: RES, such as solar and wind energy, are inherently unstable and dependent on environmental conditions. LSTM networks are designed to work with data sequences, which is ideal for modeling and predicting time series data, such as energy production depending on the time of day, season, or weather conditions.

- Long-term and short-term memory: LSTMs are capable of retaining information over longer periods, which is useful for recognizing patterns and trends in historical data, such as cyclical changes in RES energy production.
- Handling the vanishing gradient problem: In traditional recurrent neural networks (RNNs), long data sequences can lead to the vanishing gradient problem, where information from the initial stages of the sequence loses significance in the learning process. LSTMs solve this problem by using gates that regulate the flow of information.
- Flexibility in modeling dependencies: LSTM networks can model complex temporal dependencies, which is crucial for forecasting RES energy production, where production may depend on many factors, such as the intensity of solar radiation, wind speed, temperature, or humidity.
- Good results in practical applications: The scientific literature describes many cases where LSTM networks were used to forecast RES energy production and achieved better results than traditional methods, confirming their effectiveness in such applications.

In summary, LSTM networks are well suited for forecasting RES energy production due to their ability to process data sequences, handle problems associated with long temporal dependencies, and effectively model unstable and variable energy production patterns.

In the process of transforming the input sequence x = (x1, . . ., xT) into the output sequence y = (y1, . . ., yT), the LSTM network calculates the activations of the network units using a set of iterative equations. This process begins at the moment (t = 1) and continues to (t = T), where (T) is the length of the sequence. These equations are presented below:

Forget gate:

$$ft=\sigma g(Wfxt+Ufht-1+bf) \quad (1)$$

Input gate:

$$it=\sigma g(Wixt+Uiht-1+bi) \quad (2)$$

Output gate:

$$ot=\sigma g(Woxt+Uoht-1+bo) \quad (3)$$

Candidate cell state:

$$\bar{c}t = \sigma h(Wcxt + Ucht - 1 + bc) \quad (4)$$

Cell state update:

$$ct = ft \times ct - 1 + it \times \bar{c}t \quad (5)$$

Hidden state update:

$$ht=ot \times \sigma h(ct) \quad (6)$$

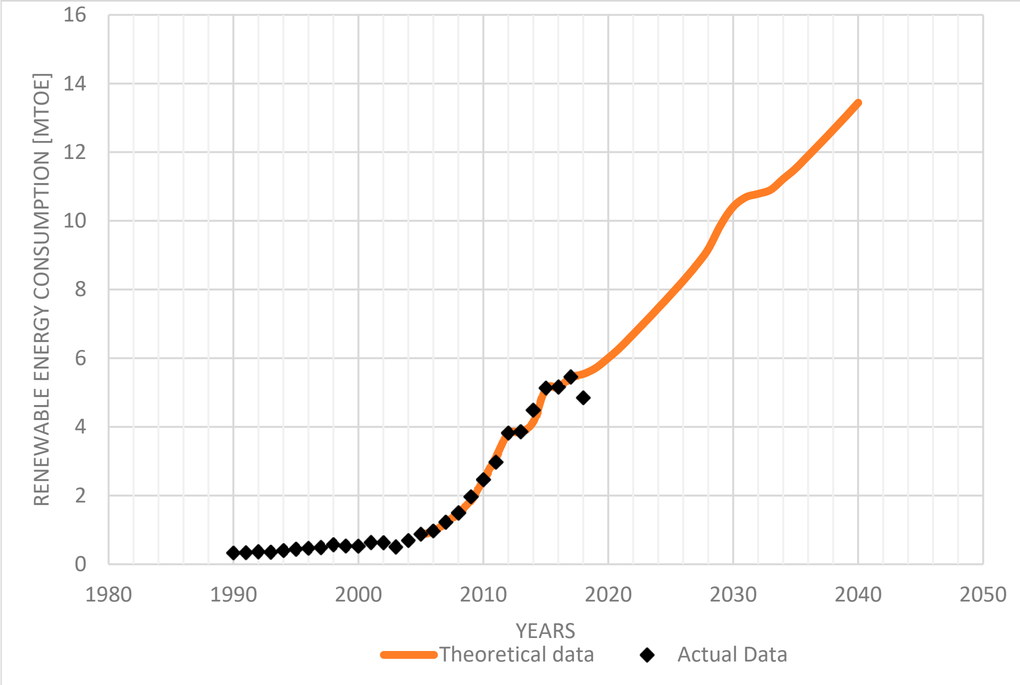
In the above equations, (W) and (U) denote weight matrices, while (bi) represents bias vectors for the respective gates. The function σ is a sigmoid activation function, and σh is a "hard sigmoid" or "tanh" activation function. The symbols (i), (f), (o), and (c) correspond to the input, forget, output gates, and cell activation vectors, respectively. All these elements have the same size as the output activation vector.

The results obtained from the model are shown in Figure 6a,b.

Based on Figure 6a,b in the document, we can draw several conclusions regarding renewable energy sources (RES):

Figure 6a presents a comparison of actual data with data generated from the LSTM model along with a forecast up to 2040. It appears that the LSTM model can be an effective tool for predicting the production of energy from RES, which is crucial for planning and managing the energy network. This model takes into account long-term trends and seasonality in energy production, which allows for better preparation of the energy system for changes in the availability of energy from RES.

(**a**)



(**b**)

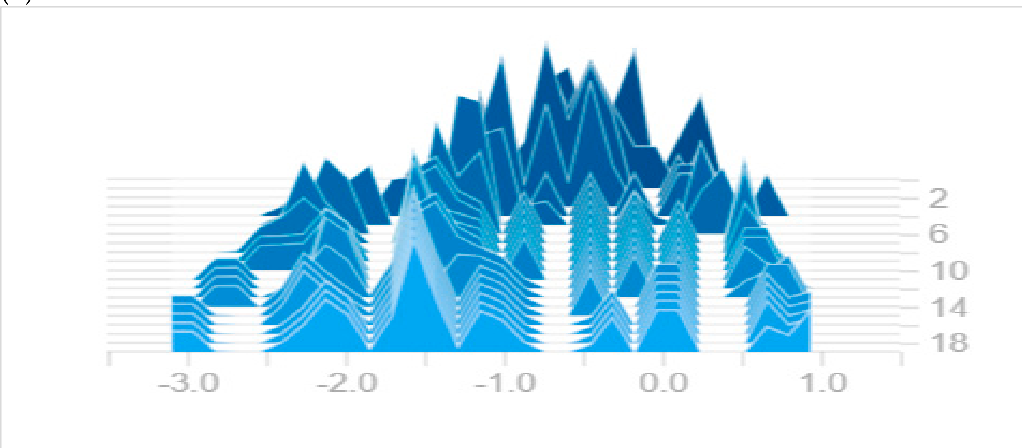


Figure 6. (**a**) Comparison of actual data and data generated from the LSTM model along with a forecast until 2040, source: own study. (**b**) Distribution of standard weights for individual iterations of network learning, source: own study.

Figure 6b shows the distribution of standard weights for individual iterations of neural network learning. These weights are important for understanding how the model processes data and which features are considered most significant for predicting the production of energy from RES. The stability of these weights over time may indicate that the model is well trained and can effectively predict future energy production.

In summary, the analysis of Figure 6a,b indicates that advanced forecasting models, such as LSTM networks, can play an important role in predicting the production of energy from RES. This makes it possible to better plan and optimize the use of RES in the energy mix, which is key to increasing the share of these sources in overall energy production and contributes to the decarbonization of the energy sector.

Due to its large resources, coal will continue to be the basic raw material for electricity production in Poland in the near future. Its share is currently dominant, as shown in Figure 7a.

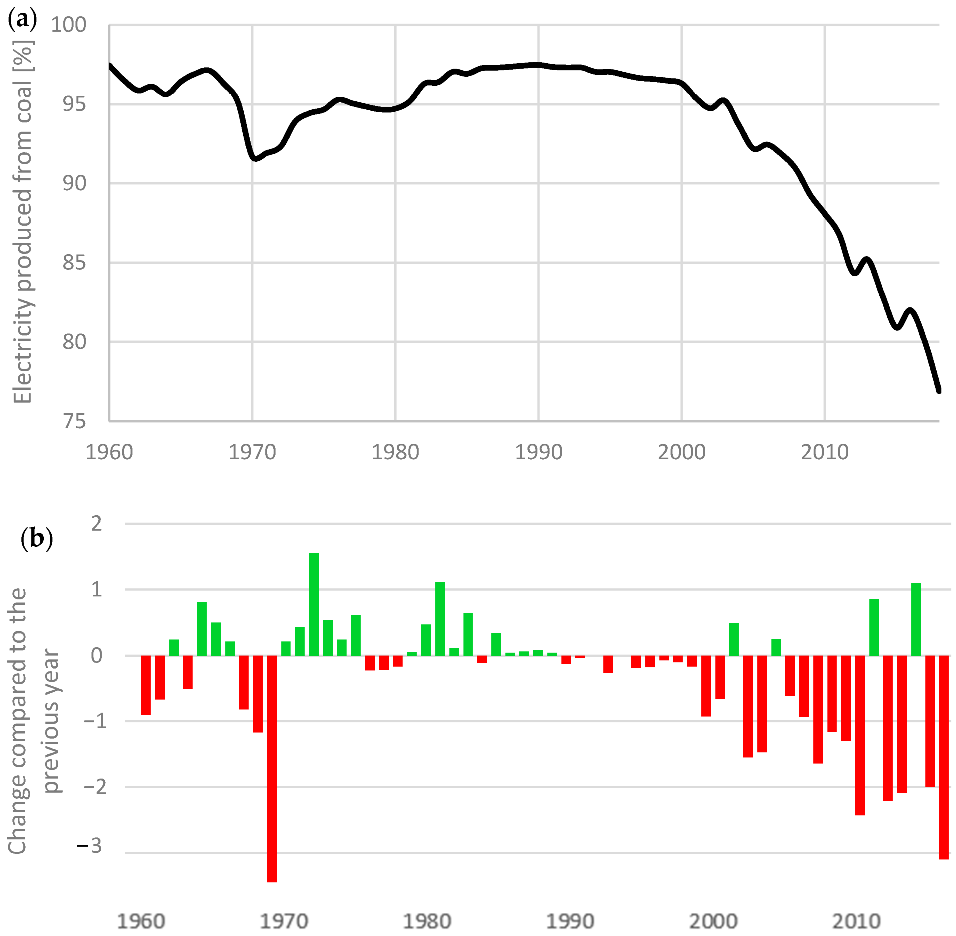


Figure 7. (**a**) Percentage share of electricity produced from coal, source: own study based on [13]. (**b**) Change compared to the previous year.

Since the 1960s, coal has been the dominant source of electricity generation, representing approximately 98% of the energy mix. However, the reliance on coal for electricity production has seen a decline after the year 2000, with the rise in the use of natural gas and the increasing incorporation of renewable energy sources into the energy mix. Despite this downward trend, coal continues to hold a significant share, which currently stands at 78%.

The challenge of reducing coal usage in electricity production by the year 2040 is significant for Poland. The objective is to markedly decrease the dependency on coal as the primary energy resource by that year, in accordance with the country's energy policy and its international climate commitments. A comprehensive approach is required, involving the expansion of renewable energy sources, the introduction of nuclear power, the enhancement of energy efficiency, and the establishment of legal and regulatory frameworks to facilitate the energy transition. These steps have been developed as part of the strategic plan to address this challenge:

- Introduction:
    - Overview of Poland's current energy mix and the role of coal.
    - The importance of transitioning to a more sustainable and diversified energy portfolio.
    - Alignment with the European Union's climate and energy goals.
- Strategic goals:
    - Reduction of greenhouse gas (GHG) emissions by 55% by 2030, compared to 1990 levels.
    - Increase the share of RES in the energy mix to at least 32% by 2030.

    - Decommissioning of the most polluting coal-fired power plants and a gradual phase-out of remaining coal facilities by 2040.
- Expansion of renewable energy sources:
    - Scale up investments in wind (both onshore and offshore) and solar photovoltaic (PV) installations.
    - Develop and implement a supportive regulatory framework for RES, including feed-in tariffs and renewable energy certificates.
    - Encourage community and regional RES projects to foster local engagement and investment.
- Introduction of nuclear energy:
    - Begin construction of the first nuclear power plant with a target operational date post-2033.
    - Establish a legal and regulatory framework for nuclear safety, waste management, and decommissioning.
    - Develop a skilled workforce for the construction and operation of nuclear facilities.
- Energy efficiency improvements:
    - Implement stringent energy efficiency standards for buildings, industry, and transportation.
    - Promote the adoption of energy-efficient technologies and practices through incentives and awareness campaigns.
    - Invest in smart grid technologies to optimize energy distribution and reduce losses.
- Legal and regulatory framework:
    - Update national legislation to reflect the goals of the National Energy and Climate Plan (NECP) and the Energy Policy of Poland until 2040 (PEP2040).
    - Introduce carbon pricing mechanisms to incentivize the reduction of coal use and promote cleaner energy sources.
    - Ensure a just transition for workers and regions affected by the coal phase-out, providing retraining and social support programs.
- Research, development, and innovation:
    - Invest in research and development (R&D) of new energy technologies, including energy storage and carbon capture and storage (CCS).
    - Foster partnerships between government, academia, and industry to accelerate innovation and commercialization of clean energy solutions.
- International cooperation and funding:
    - Seek collaboration with international partners for technology exchange and joint R&D projects.
    - Access European Union funds and other international financing mechanisms to support the energy transition.
- Monitoring and evaluation:
    - Establish a monitoring framework to track progress towards the strategic goals.
    - Conduct regular reviews and adjust strategies as necessary to meet targets and respond to technological advancements.

The successful implementation of this plan will require strong political will, substantial investment, and the cooperation of all stakeholders. By reducing the use of coal and embracing cleaner, more sustainable energy sources, Poland can achieve its environmental objectives, enhance energy security, and contribute to the global effort to combat climate change.

3. Energy and Climate Policy

Poland's energy policy focuses on reducing carbon intensity through various measures. These include increasing the utilization of renewable energy sources and natural gas, introducing nuclear energy, promoting electrification of energy demand, particularly in the transportation sector, and enhancing energy efficiency. Energy security and a just transition are key priorities for Poland, ensuring access to affordable energy while fostering economic growth and safeguarding vulnerable consumers [14–19].

The primary frameworks outlining Poland's energy and climate policy are the National Plan for Energy and Climate (NECP) and the Energy Policy of Poland until 2040 (PEP2040). The NECP, which was adopted in 2019, is a requirement for all EU Member States. PEP2040, on the other hand, was adopted in February 2021 [20,21]. These documents provide strategic guidelines and goals for Poland's energy sector, aligning with the country's commitment to sustainable and environmentally friendly energy practices.

The unit emissivity of primary energy consumption was as follows (Figure 8):

- In 2020, Poland was ranked 6th in the world in terms of emissivity of primary energy consumption.
- South Africa had the most emission economy (3.18 t CO_2/toe).
- Poland, with a result of 2.85 t CO_2/toe, ranked just behind China (2.87 t CO_2/toe). For comparison: the British economy emitted 31% less than Poland (1.97 t CO_2/toe), and the French economy 56% less (1.25 t CO_2/toe).

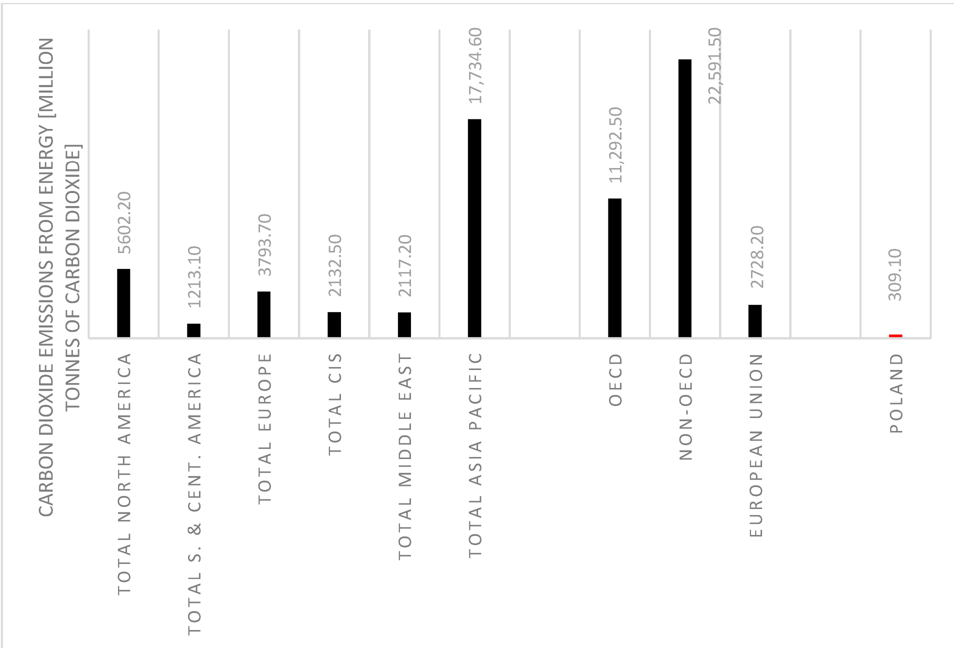


Figure 8. Unit emissivity of primary energy consumption, source: own study based on [11].

The emissivity of electricity production in 2020 in Poland amounted to approx. 710 kg CO_2/MWh and was one of the highest in the European Union. Such high emissivity has and will have an impact on the industry, e.g., due to the growing importance of the carbon footprint in production or the high sensitivity of electricity prices to the prices of CO_2 emission allowances.

The structure of greenhouse gas emissions in Poland was as follows (Figure 9):

- In 2020, most emissions came from the production of electricity and heat–35.1% of total gross emissions.
- Transport and industry accounted for 16.9% and 16.5%, respectively.
- Households emitted 9% of greenhouse gases.

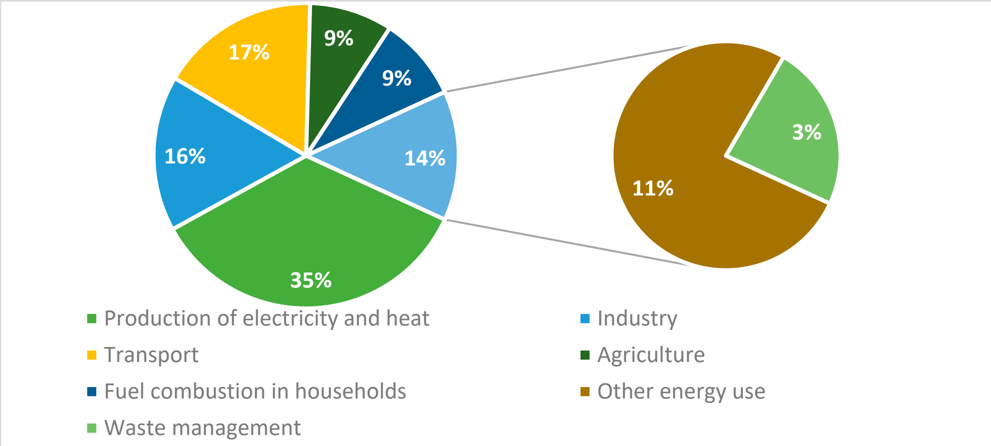


Figure 9. Structure of greenhouse gas emissions in Poland, source: own study based on [22].

In compliance with national legislation and EU directives, Poland has established a comprehensive set of energy and climate targets for 2030. The European Union Emissions Trading Scheme (ETS) regulates greenhouse gas (GHG) emissions from energy-intensive industrial plants and electricity production in Poland. The Polish National Plan for Energy and Climate (NECP) outlines specific targets for 2030 related to GHG emissions not covered by the ETS, renewable energy, and energy efficiency. These targets aim to contribute to the broader EU-wide objectives for 2030.

The Energy Policy of Poland until 2040 (PEP2040) encompasses a range of goals for both 2030 and 2040, serving as benchmarks for monitoring the progress of Poland's energy transformation. In December 2020, the EU increased its target for greenhouse gas emissions reduction to 55% by 2030, prompting the development of more ambitious targets for renewables and energy efficiency. Consequently, Poland is likely to adjust its 2030 targets and implement additional measures to support the EU-wide objective of 55% emissions reduction.

Poland has implemented various measures to facilitate the energy transformation while prioritizing energy security. Significant efforts are being made to reduce the reliance on coal for electricity and heat production by steadily integrating renewable energy sources and natural gas while introducing nuclear energy. The Polish Nuclear Energy Program outlines the strategy, schedule, and safety protocols for the implementation, decommissioning, and waste storage of nuclear energy. Poland aims to launch the first reactor with a capacity of 1–1.6 GW by 2033 and expand to six reactors with a total capacity of 6–9 GW by 2043. The government estimates that nuclear energy could account for up to 16% of the overall energy generation by 2040.

Polish coal-fired power plants produce on average 16 GW of electrical power [23]. In order to replace all Polish coal-fired power plants with nuclear power plants, 5–6 nuclear power plants would have to be built. This gives a cost of approximately USD 100–120 billion. This is a huge cost for a medium-sized European country. Therefore, the question arises: Is the cost of constructing and operating an energy storage facility enabling the entire country to be supplied exclusively from renewable sources less than the cost of constructing and operating nuclear power plants? The results of the analyses presented below allow an approximate answer to this question.

4. Share of Nuclear Energy and Renewable Energy Sources in the Energy Market

Nuclear power is a low-carbon alternative to fossil fuels and is a significant component of the energy mix of 13 out of 27 EU Member States, accounting for almost 26% of the electricity produced in the EU. As of April 2023, there are a total of 167 nuclear reactors operating in Europe with a net installed electrical capacity of 147,619 MWe (6 of them in the Asian part of the Russian Federation) and 11 units with a net electrical capacity of 12,709 MWe were under construction in six countries [23]:

- Belarus—1;
- France—1;
- Russia—4;
- Slovakia—2;
- Ukraine—2;
- Great Britain—2.

In terms of electricity generated globally from nuclear power in 2021, France is in first place with a share of 69%, followed by Ukraine (55%) and Slovakia (52.3%), followed by Belgium (50.8%).

Poland is currently facing a huge energy transformation. Diversification of the energy mix, ensuring energy security, reducing the impact on the environment, while maintaining the competitiveness of the economy, involves huge investment outlays. Renewable energy sources, such as windmills or photovoltaic panels, are good support for our system, but they are not entirely sufficient, because due to their specificity, they cannot produce energy continuously. Therefore, the best solution for the Polish energy sector is to invest in nuclear energy.

The structure of Poland's energy mix is similar to the Czech Republic (as shown in Figure 10), and in this country they have as many as six efficient reactors: two units are in Temelin, 100 km south of Prague; and four Dukovany units, 34 km west of Brno. The long-term energy policy, which was adopted in 2015, takes into account the need to increase the share of nuclear energy to 50–55% of the energy mix by 2050 in order to avoid dependence on electricity imports from 2030. The Czech company CEZ confirmed the construction of four units in Dukovany by 2045 and 2047, and two units in Temelin by 2060 and 2062. According to the current schedule, it is expected that the supplier will be selected in 2022 and the license will be issued in 2029.

(a)

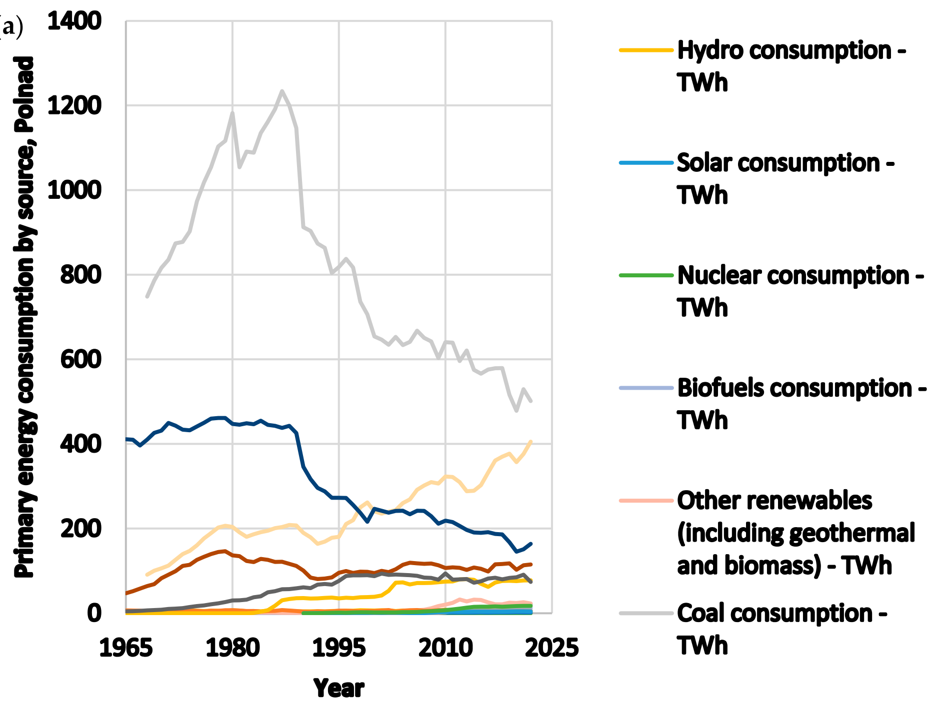


Figure 10. *Cont.*

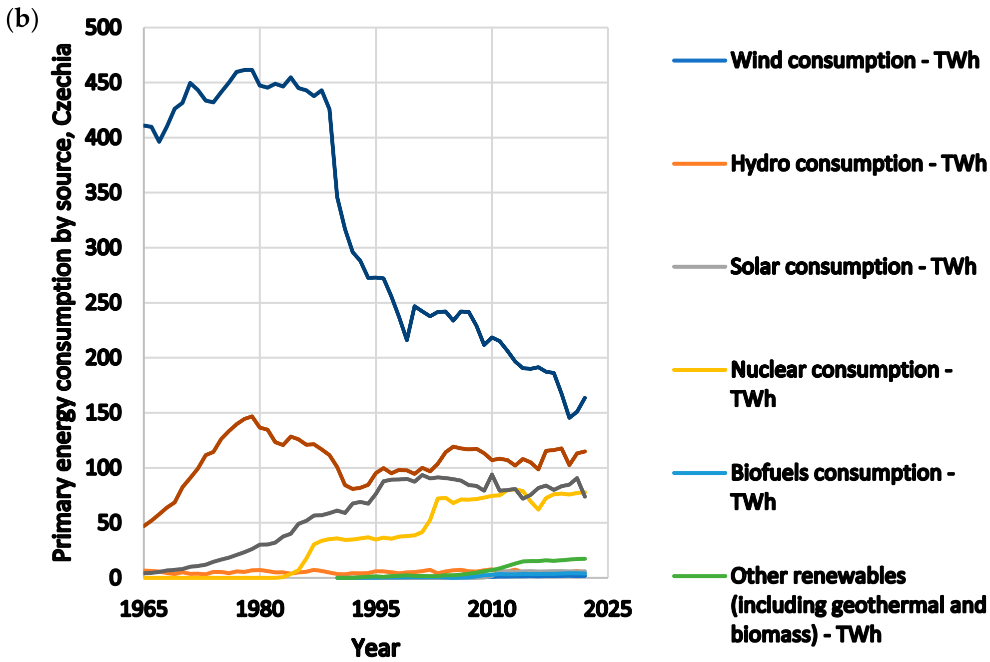


Figure 10. (**a**) Energy mixes of Poland own study based on [11]. (**b**) Energy mixes of the Czech Republic, own study based on [11].

5. Materials and Methods

Table 1 presents the power generated in Poland in thermal (mainly coal-fired) power plants and renewable energy sources on 22 May 2023 at 12:30 p.m. These results were determined based on measurements provided by the Polish Electricity Agency (PSE S.A.) [22]. That exemplary day was sunny in Poland—cloud cover 20~30% (sunny or scattered clouds), temperature ~23 °C, and wind speed 20~30 km/h. The table below does not include all pumped-storage power plants, so the sum of the generated power and the actual total cross-border exchange power does not exactly give the total load power.

Table 1. Total power generated in Poland by various types of power plants on 22 May 2023 at 12:30 PM.

Power Type	Power, MW
Total grid load	20,567
Generation total	20,057
Thermal power plants	10,823
Water power plants	218
Wind power plants	734
Photovoltaics	8282
Other renewables	0
Actual total cross-border exchange	480 (import)

It should be noted that all renewable energy sources produced 9234 MW, and it was slightly less compared to the power produced in all Polish thermal power plants—10,823 MW on that day. It was a very good result—renewable sources produced almost half of the power in the national electricity grid on a sunny day at noon. However, at this point, there is a significant problem for the further development of photovoltaics in Poland. It should be clarified that photovoltaic system in Poland are scattered and based mainly on household solar panels. Large solar farms managed by energy companies are in the minority. As a result, in the middle of sunny days, the voltage in the local low-voltage grids increases to almost 250 V (nominal value 230 V 50 Hz) and then is necessary to partially switch off household solar panels or solar farms. This is a significant problem in the further development of photovoltaics in countries such as Poland. Thermal power plants are characterized by high inertia—they cannot be quickly turned off and on. The power plant unit must be started or shut down in a planned manner—e.g., seasonally or for the period of pre-planned service works. Further development of photovoltaics is possible only if large energy storage facilities are used.

The Figure 11 shows the daily power load of the electricity grid in Poland for two exemplary days: 21 May 2023 (Sunday—day off in Europe) and 22 May 2023 (Monday—working day). The graph in the Figure 11 was determined on the basis of measurements provided by PSE S.A. [22,23]. The weather was the same on both days.

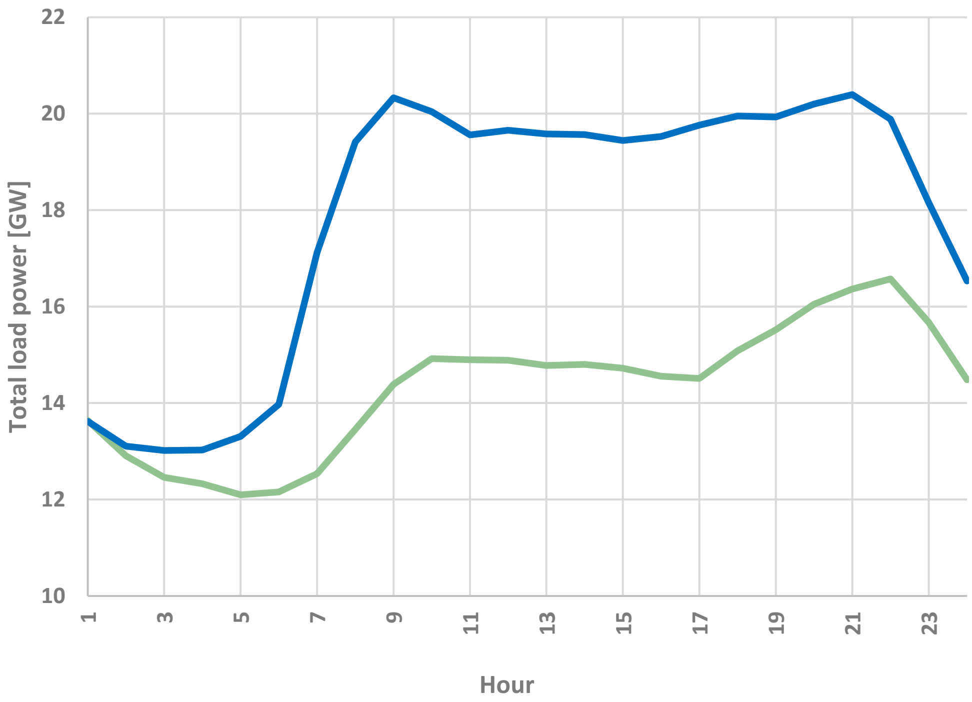


Figure 11. Daily power load of the electricity grid in Poland for two exemplary days: blue line—Sunday, green line—Monday, source: own study.

The chart in Figure 11 indicates that the total power load on working day at 9 o'clock and 21 o'clock is almost twice as large as compared to 3 o'clock in the night. Since solar power plants do not produce electricity at night, it is necessary to use coal-fired power plants with a total power of at least 10 GW around the clock. In the future, coal power plants will be replaced by nuclear power plants. However, it is not necessary to replace all coal-fired power plants with nuclear ones. If large energy storage facilities equipped with supercapacitors were used, there would be no need to build many of the expensive nuclear power plants.

6. Results and Discussion

The previous research results presented in paper [24] have shown that it is possible to power the entire country based solely on solar farms. To make it feasible, it is necessary to use sufficiently large energy storage. Of course, such an energy storage would not be located in one place, but would consist of many local storage facilities located next to solar farms or switching stations. In addition, energy storage must have a sufficiently high energy efficiency and lifetime. So far, photovoltaic systems use energy storage based on rechargeable Li-Ion or acid batteries. Unfortunately, rechargeable batteries have a short lifetime—depending on the operating conditions, a Li-Ion battery has a lifespan of several thousand cycles (charge—discharge)—this issue is discussed in more detail in [25]. If the batteries are used optimally—charging to max. 60% and discharging to min. 30%, it is possible to extend their service life up to three times. However, in that charging-discharging configuration, the useful capacity of the energy storage (based on Li-Ion) is clearly lower—approximately 30% of the nominal value. High charging or discharging current values (1C and more multiples of capacity) significantly shorten the battery lifetime. High current also causes unfavorable thermal effects (additional heating), which has a negative impact on the cell. All the above factors mean that after a year or at most a few years it is necessary to replace all Li-Ion batteries in the energy storage unit. Recycling of worn out batteries requires energy and generates an additional carbon footprint. The short lifetime of batteries and the need to recycle them is their greatest inconvenience. Consequently, batteries generates the natural environment burden.

From a practical perspective, rechargeable batteries cannot be used to build a large energy storage facility to power an entire country. The solution to this problem appeared several years ago and is being intensively developed—supercapacitors (SCs) for energy storage systems. This may seem surprising, because supercapacitors have several times lower stored energy density compared to batteries—typically batteries have energy density between 150 and 500 Wh/kg [26]. Supercapacitors have a significant advantage from the point of view of use in energy storage—a lifetime of hundreds of thousands of cycles (typically more than 500,000) and the ability to charge and discharge much faster than batteries [26,27]. In addition, the energy efficiency of the charge-discharge process in SCs is 85~98%. This is much more than in batteries 70~80% [27]. Disadvantage of SCs—lower energy density is not a problem with energy storage. This is a problem for vehicle applications—which is why batteries are still used in electric cars. It should be added that some electric cars, trains, and trams have SCs to recover energy during braking, but these capacitors are not the main source of power. One of the advantages of SCs is used here—the possibility of fast charging and discharging. Returning electricity generated during braking to the railway traction network is effective only if there is another train nearby that could consume this energy. A major disadvantage of SCs is their voltage characteristics during discharge—theoretically, in the case of a resistive load, the voltage at the capacitor terminals decreases exponentially (it is a fast process). In the case of batteries, the voltage drop is slow and during the entire discharge process used, the voltage decreases only by 10–20% from the initial value. This is no longer a technical problem. Inverters are widely available, including those adapted to work with supercapacitors (these inverters are based on fast IGBT and MOSFET transistors—today is not a problem). Thanks to this, despite the unfavorable characteristics of the supercapacitor, the amplitude of the output voltage at the inverter terminals can maintain a stable value.

It should be noted that the goal is not to find any energy storage that would enable the operation of RES. The goal is to decarbonise while ensuring continuity of electricity supply. Currently, lithium-ion batteries are still the most popular for energy storage. Since the production of Li-Ion cells causes significant greenhouse gas emissions (in 2020 it was 41–89 kg CO_2 eq per 1 kWh Li-Ion battery [23]), the rechargeable batteries in general do not favor the decarbonisation process. The world's lithium resources are not unlimited, and the extraction and processing of lithium ores also requires energy. Meanwhile, lithium recovery from used cells is still low. In 2020, the European Commission gave recommendations for a regulation concerning batteries (Annex XII). According to that proposal, in 2026 the level of material recovery should be: 35% for lithium and 90% for nickel [28] and these values should increase in subsequent years. Significant emissions of CO_2 and other greenhouse gases accompany the production of rechargeable batteries. The authors in [29] analyzed the greenhouse gas emissions of automotive lithium-ion batteries. That paper shows, among others, relationship based on literature analysis of the observed GWP (global warming potential) kg CO_2 eq. per 1 kWh capacity for different the battery specific capacity varies from 50 to 300 Wh/kg. Considering the wide scope of the literature, there were also clear differences in the estimated value of kg CO_2/kWh depending on the geolocation of the authors (of the analyzed literatures). The paper [29] graphically shows the variation of kg

CO_2/kWh for authors affiliated in America, Europe, and China. That distribution takes into account the battery manufacturing energy in MJ/kWh. The paper [29] provides more detailed data compared to [23], but final conclusions for batteries with high-battery specific capacity (more than 200 Wh/kg) are similar and the greenhouse gas emissions cover range 30–80 kg CO_2 eq./kWh. Generally, it is very difficult to accurately estimate CO_2 eq. emissions during batteries production process—there are many indirect factors and not all of them are always taken into account. it should be noted that most researchers believe that the value of CO_2 eq. emission is significantly high. In the work [30], the authors simulated lifecycle emissions for five commercial lithium chemistries. They estimated emissions from battery production of 194–494 kg CO_2 eq. per 1 kWh of Li-Ion battery capacity. That shows how wide the discrepancies are in the results presented by different researchers.

Rechargeable batteries (mostly Li-ion) are essential in powering vehicles. Large-scale use of Li-Ion batteries in energy storage facilities with the capacity necessary to power the entire country would probably result in a shortage of these batteries on the market. Rechargeable batteries should be used primarily in electric vehicles.

However, for energy storage with renewable energy sources, SCs are the best solution. SCs have only been gaining popularity for a few years. Unlike batteries, SCs do not require lithium, nickel, or lead in the production process. The technology of their production is based to some extent on the production of electrolytic capacitors, which have been well known and widely manufactured for a long time. Supercapacitor technology is still evolving.

There are generally three different types of supercapacitors:

- EDLCs (electrochemical double-layer capacitors)—these capacitors are based on electrostatic interactions on two conducting electrodes (carbonaceous materials) and double layer at the electrolyte-electrode contact area. EDLCs offer fast charging and discharging, power density of 20 kW/kg or much higher and maximum energy density of 10 Wh/kg [27,28,31–34],
- Pseudocapacitors—an electrical energy is stored thanks to reversible oxidation-reduction (redox) reactions. These capacitors have a capacitance more than one order of magnitude higher than that of the EDLCs [31–34].
- Hybrid supercapacitors. This is an intermediate solution between a supercapacitor and an Li-Ion battery. The first electrode uses redox reactions, exhibiting battery-like electrochemical behavior, and the second is a capacitor-type electrode [31,35]. They have high specific energy, but also lower number of recharge cycles.

High prospects are associated with the electric double-layer capacitors (EDLCs) and pseudocapacitors. Their main advantage is the high number of recharge cycles—half a million to a million. Moreover, they are lithium and nickel free. EDLCs and pseudocapacitors are good candidates for the large energy storage facilities capable of powering the entire country. Their long lifetime and successively decreasing price are the main advantage. Significantly larger sizes of SCs in relation to Li-Ion batteries and hybrid SCs are not a disadvantage in stationary energy storage applications. It should be noted the very rapid development of SCs technology. Specific energy coefficient in SCs has been increasing in recent years. Research on new materials and nanomaterials for the production of electrodes is particularly important for the development of SCs. In particular, authors in paper [36] present investigation of the influence of iridium content on the charge storage in SCs. The paper [37] shows nickel oxide on directly grown carbon nanofibers for energy storage applications. Research on new materials for electrodes is extremely important because it influences the increase in the capacity of SCs in the coming years. The latest developments in SCS technology have been extensively described in [38]. In that paper, the authors show an example where supercapacitors have been introduced as replacements for battery in energy storage in PV systems.

Fuel cells and hydrogen storage can also be used in the energy storage process. Currently, hydrogen-powered cars and trains are commercially available. In recent years, it has become possible to use not only hydrogen in the energy storage process, but also methanol and ammonia—this issue has been thoroughly discussed in paper [39]. The use of methanol and ammonia is interesting from a practical point of view. Hydrogen, due to the small size of its molecules, easily penetrates through the walls of any tank. Storing it for a long period of time would result in losses in the amount of stored gas. Moreover, hydrogen is extremely flammable. In the case of methanol and ammonia, the storage problem is clearly simpler. Hydrogen and fuel cells will be partially used in large energy storage facilities. However, the energy efficiency of fuel cells in the hydrogen production process and nest in the electricity production (~60% max.) is significantly lower than the energy efficiency of charging and discharging SCs (~95% max.). In addition, hydrogen storage facilities require advanced safeguards to prevent possible explosions.

The efficiency and lifetime of energy storage based on SCs depends significantly on the temperature and operating conditions. Experience and literature analysis have shown that favorable operating conditions for SCs occur in a temperature range of approximately from −10 °C to 20 °C [40,41]. SCs can operate outside that temperature range but this results in a shorter lifetime. Particularly unfavorable is the increase in operating temperature above 30 °C. At a temperature of 70 °C, the lifetime of SCs decreases up to 10 times compared to room temperature. This is a very unfavorable phenomenon. High temperature can also cause a decrease in SCs capacitance. However, it should be noted that batteries (of any type) cannot safely operate above 50 °C (they may explode). Therefore, SCs require a similar operating temperature to batteries. The advantage of SCs over batteries is high efficiency in the low temperature range. To ensure a long lifetime of SCs, they should be operated below room temperature. A very good location for energy storage based on SCs are underground coal mines. The temperature of the rock in the mine at a depth of 300 m below the ground surface is typically in the range of 15 °C to 20 °C depending on the season (in recent years, the air temperature in winter drops to −10 °C, and in summer it rises to 35 °C). In deep mines (more than 1000 m deep) the temperature of rocks is less than 30 °C and is independent of the season. The true air temperature at this depth in the mine is typically 35 °C—this is not the result of natural phenomena, but the power of tens of megawatts given off by underground machinery. Nowadays, coal mines are systematically closed down. There are still several dozen coal mines in Poland. In a few years, almost all of them will be closed. It should be noted that the liquidation of a coal mine is a complicated and expensive process. The sudden interruption of mine operation and the shutdown of all machinery and equipment leads within a few months to an ecological and construction disaster. Underground water accumulates in a closed mine. In a closed mine, underground water quickly accumulates. This causes the tunnels to blur and the ground to collapse. As a result, the buildings on the ground are skewed. In the next stage, sinkholes are formed and buildings, streets, and railway lines crack. Therefore, even in a closed coal mine, water is still being pumped out to prevent a catastrophe. As a result, the construction of underground energy storage in closed mines will not generate additional financial costs; the water pumps must work independently of the fate of the closed mine. The idea of building an underground energy storage in closed mines was previously discussed in [39]. According to those analyses, the estimated volume of a typical Polish coal mine underground is in the order of 10^7 m^3. That gives an underground volume of more than 0.2–0.6 km^3 for about 20 closed mines (there are many more mines in Poland that will be closed in the future). The closed mines are really perfect locations for large energy stores.

Another important parameter of SCs is ESR (Equivalent Series Resistance). The aging of the SCs causes the ESR value to increase. The flow of current through the resistance ESR (during charging and discharging of the capacitor) causes the release of heat in it. This, in turn, increases the SC temperature and accelerates the aging process. This unfavorable phenomenon is particularly noticeable during fast charging or discharging in electric vehicles—energy recovery during braking takes only a few seconds. A high value of the current causes a significant increase in temperature (the power dissipated in the ESR resistor depends on the square of the charging/discharging current). In the case of stationary energy storage, the process of charging and discharging takes several hours. This is a very important difference between the SCs in electric vehicles and the energy storage proposed in this paper. By applying the appropriate algorithm for the operation of individual sections in the energy storage, it is possible to obtain a low current in the SCs cells. As a result, the power dissipated in the ESR resistors in SCs is low and not cause a significant increase in temperature. Of course, there are many other technical problems related to the operation of SCs, such as reactive power compensation in the power grid (voltage converters, DC-AC inverters, filters etc.). These problems, however, are very similar to those that occur with battery power systems and do not constitute a barrier to the development of supercapacitors for large energy storage.

Figure 12 presents the concepts of using SCs in the energy market in Poland. The use of SCs allows the construction of large energy storage facilities capable of operating for decades. This makes it possible to increase the share of renewable energy sources in the energy mix. Without the participation of sufficiently large energy storage facilities, it would be impossible. SCs are next generation energy storage [29]. SCs are integrated seamlessly with solar and wind farms. Nowadays, inverters with high energy efficiency (also more than 90%) are widely available. A properly designed inverter can be easily integrated with SCs. There are many examples of ready-to-use solutions integrating SCs with wind farms and PVs and development research in that field [42–46].

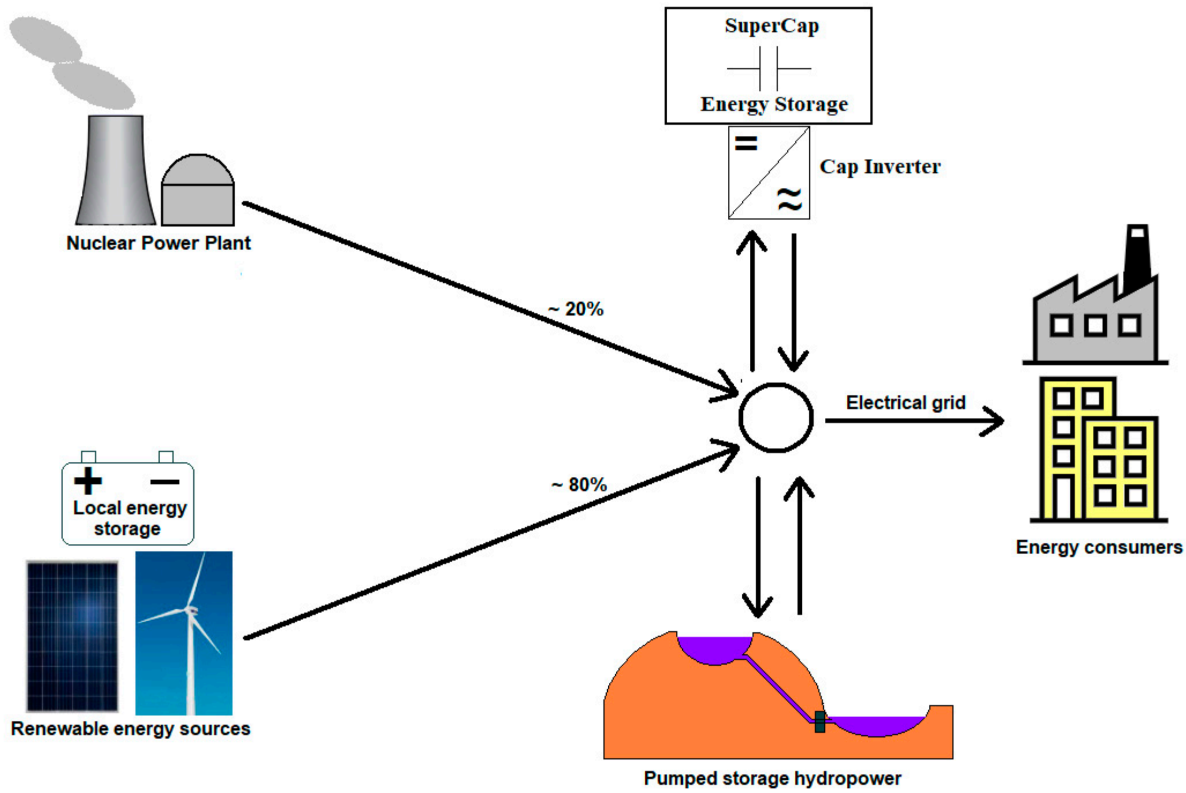


Figure 12. The proposed structure of the energy market in Poland after the closure of coal-fired power plants, source: own study.

The development of wind farms requires further optimization of wind turbines in the current period [47].

The electricity consumption in 2019 (before COVID-19 pandemic) was 165.7 TWh in Poland [19]. Taking the most unfavorable case, in which all consumed energy must be stored at an intermediate stage, it is possible to estimate the capacity of the energy storage and the amount of energy necessary to produce it. If a typical level of consumption is approximately E_{year} = 170 TWh per year and the energy efficiency of the electricity storage process (including the efficiency of the inverters) at the level of 60%, about 283 TWh of electrical energy should be produced in Poland annually (170 TWh/0.6 ≈ 283 TWh)—that issue is discussed in more detail in paper [26].

The high share of renewable energy sources in the energy market (~80% like in Figure 12) requires the use of appropriately large electricity storage. The daily changes in the power generated by RES are not the most important problem in estimating the capacity of this electricity storage. An important problem arises when RES generate significantly too low power for several consecutive days—a series of several windless and cloudy days. In Central Europe, that phenomenon is observed every year or every few years in autumn or winter. During these seasons, the days are short, and the sun angle is low. Consequently, if there are windless days in autumn or winter, the total power generated by RES are very low.

Today, those series of several windless and cloudy days are not a big problem while coal-fired power plants are still operating. When the vast majority of electricity will be generated from RES, the weather will have a much greater impact on the operation of the power grid (in a few years, coal power plants will be shut down and only some of them will be replaced by nuclear power plants). Therefore, the analysis of multi-days of electricity production from RES is very important. Since 2013, the Polish Electricity Agency (Polskie Sieci Elektroenergetyczne) [48] has provided important data on energy production from photovoltaic and wind power plants for every hour and every day of the year. The database is available at link [39]. Unfortunately, today the website [39] supporting this database is only in Polish. Taking into account the most unfavorable variant when the entire country is powered only by renewable energy sources (without taking into account the power generated by nuclear power plants), the necessary energy storage capacity could be estimated in (Equation (7a)). This equation describes the capacity of electricity storage necessary to power the Polish electricity grid for "d" days exclusively from that energy storage. The parameter "d" is a number of days in a series when RES do not generate electricity (in practice, they generate very low power on windless and cloudy days). The average length of the year is assumed to be 365.25 days in Equation (7a,b).

$$E_d = \frac{d}{365.25} \cdot \frac{E_{year}}{\eta} \tag{7a}$$

where

E_d—capacity of energy storage necessary to power all Polish power grid for "d" days when RES do not generate electricity;

E_{year}—average level of annual electricity consumption in Poland (currently it is approximately 170 TWh per year);

η—energy efficiency of the electricity storage process (including the efficiency of the inverters and charging and discharging of supercapacitors);

d—the length of a series of days when RES do not generate electricity.

The value of the "d" parameter was determined empirically based on the following analysis of annual electricity production from wind and solar farms. Diagrams in Figures 13–15 were calculated on the basis of hourly electricity production data for various RES power sources in Poland (wind farms, PVs, etc.). Those hourly data are made available by PSE [48]. Figure 13 shows daily energy generated by wind farms (Ewind) in Poland in the period from 1 September 2022 to 31 August 2023. That period includes all seasons. The chart below shows that wind farms generate the most power in winter (December–February) and early spring. In other seasons it is smaller. Even though the graph shows a period of 365 days, this pattern was usually repeated in previous years.

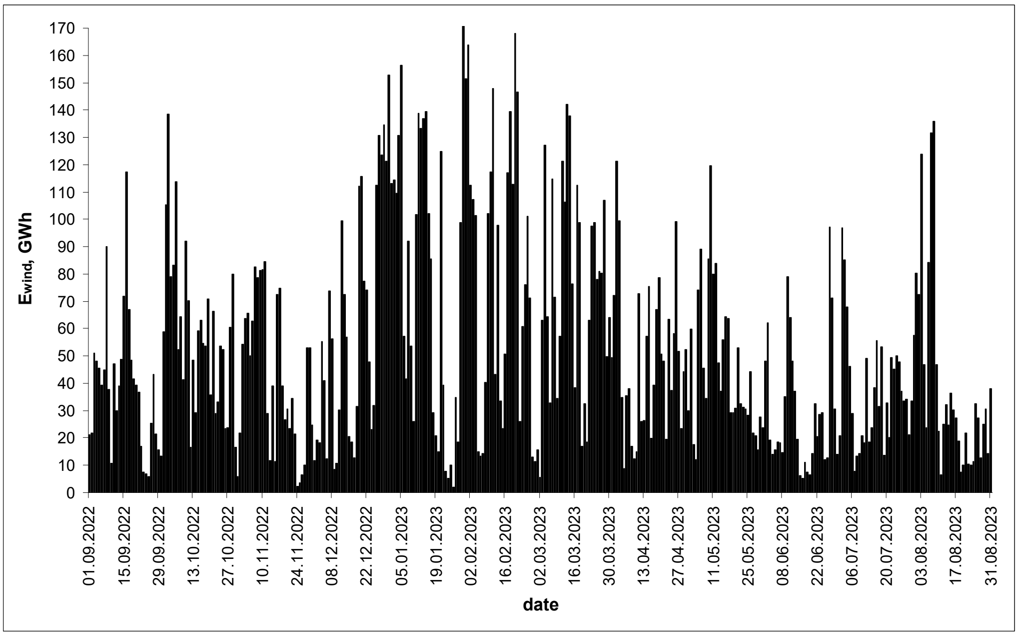


Figure 13. Daily energy generated by wind farms in Poland in the period from 1 September 2022 to 31 August 2023.

The graph in Figure 14 shows daily electrical energy generated by PVs (it is labeled as Epv in Figure 14). Poland is located at a latitude ranging approximately from N49°00′ to N54°50′. Therefore, there is a large disproportion between summer and winter in the length of the day and in the angle of incidence of sunlight. During winter, PVs produce electricity effectively for only 4–5 h a day. Photovoltaics generate much more energy in the summer. Based on the data in Figures 13 and 14, the sum of daily electrical energy generated by PVs and wind farms was calculated—total daily produced energy by all these types of sources. That sum is presented in Figure 15 and is labeled as E_{tot}.

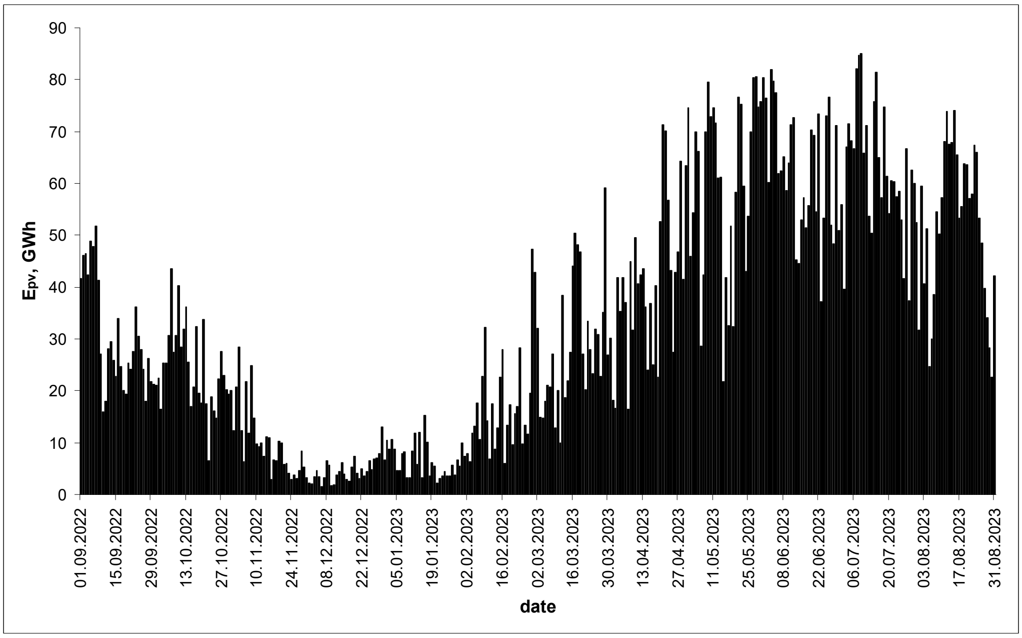


Figure 14. Daily energy generated by PVs in Poland in the period from 1 September 2022 to 31 August 2023.

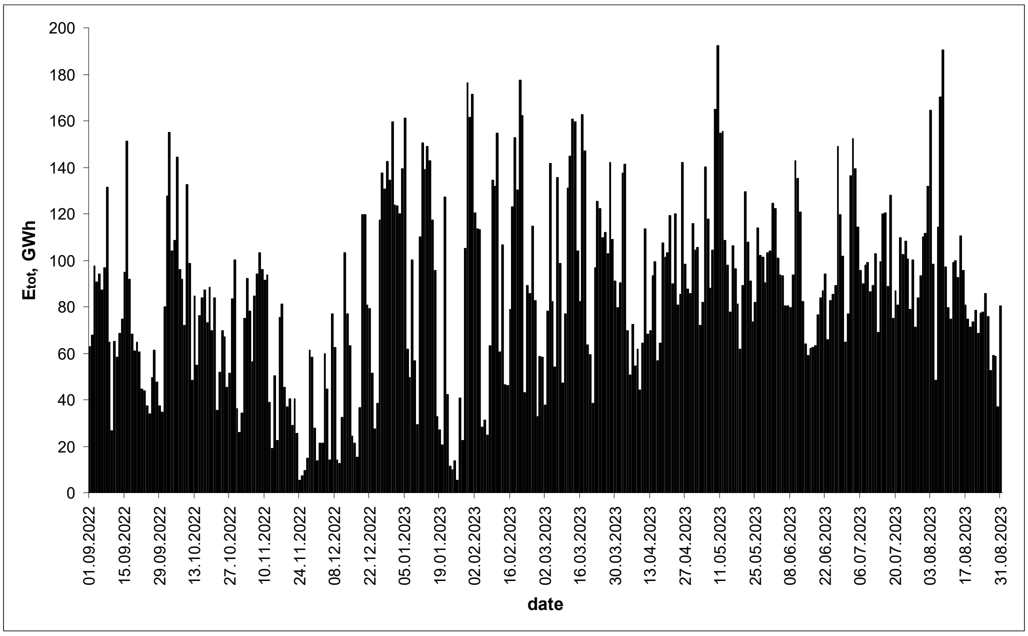


Figure 15. Daily total energy generated by wind farms and PV sources in Poland in the period from 1 September 2022 to 31 August 2023.

The arithmetic mean (average) was calculated for the numerical data from the graphs in Figures 13–15. The results are presented in Table 2. During meteorological summer, electricity production from PVs sources is 6.62 times higher than in meteorological winter. The opposite trend is for wind farms—during summer they produce more than 2 times more electrical energy as compared to winter. These differences between PVs and wind farms are very important. The total power generated by PVs and wind farms shows much less seasonality than each of them separately—Figures 13 and 14 vs. Figure 15. This is also confirmed by the results in Table 2.

Table 2. Results of the obtained average daily electrical energy generate by wind farm and PVs sources in Poland.

Average Daily Generated Energy in the Period:	Wind Farms, GWh	PVs, GWh	Wind Farms & PVS, GWh
365 days (1 September 2022–31 August 2023)	52.70	33.40	86.10
Summer (1 June 2023–31 August 2023)	35.64	58.91	94.55
Winter (1 December 2022–28 February 2023)	73.28	8.90	82.18
Summer to winter energy ratio	0.49	6.62	1.15

Taking into account the results in Table 2 and the data in the graphs in Figures 13–15, the number of days in which total daily energy was generated above average was determined: 179 for 365 days (in the period 1 September 2022–31 August 2023); 41 out of 90 days in meteorological winter and 52 out of 92 days in meteorological summer [48].

Summer to winter generated energy ratio (for both sources together) is about 1.15. Moreover, the analysis of long-term (multiannual) results shows that every few years an unfavorable phenomenon occurs in autumn or winter—a series of several or a dozen cloudy and windless days. The data presented in Figure 15 contain two such unfavorable series—approximately 23 November 2022–28 November 2022 and 22 January 2023–27 January 2023. During the entire period under consideration, from September 2022 to August 2023, there were only two such series. In each case, the length of a single series was shorter than 7 days. At the turn of 2021 and 2022, the period of uninterrupted windless and cloudy weather did not exceed 5 days. Taking into account the above average values and the data in the charts in Figures 13–15, the parameter "*d*" in Equation (7a) should be taken as $d \leq 7$. This value is the most unfavorable variant of "*d*" parameter. Substituting d = 7, E_{year} =170 TWh [24] and η = 0.6 (η =60%) into Equation (7a) give below Equation (7b).

$$E_7 = \frac{7}{365.25} \cdot \frac{170}{0.6} \approx 5.43\ TWh \tag{7b}$$

where

E_7—capacity of energy storage necessary to power the Polish power grid for d = 7 days when RES do not generate electricity.

The above energy storage (capacity 5.43 TWh) allows for an 80% share of renewable energy sources in the electricity energy mix in Poland (according to schematic in Figure 13). This will ensure the power supplied by five nuclear power plants—it means that 5.43 TWh energy storage together with RES allows avoiding the construction of five nuclear power plants.

The cost of building one nuclear power plant with three Westinghouse AP1000 reactors is approximately USD 20 billion. This adds up to USD 100 billion in total = 10^{11} USD. For the construction of an energy storage to be competitive (more profitable) compared to the construction costs of a nuclear power plant, the unit cost of storing 1 Wh for a period of 7 days must not be higher than the value in Equation (2). The energy storage capacity necessary to provide power to Poland of 7 days is determined in Equation (7b) and is equal to 5.43 TWh = $5.43 \cdot 10^{12}$ Wh. Hence, in Equation (8), it was assumed that the energy storage based on supercapacitors should have the capacity for a seven-day national electricity consumption including energy losses in the storage process.

$$E_{1Wh-\cos t} = \frac{10^{11}}{5.43 \cdot 10^{12}} \approx 0.018\,\frac{\$}{Wh} \tag{8}$$

Moreover, the large capacity of the energy storage gives the opportunity and time to run an oil-fired reserve power plant. Such power plants are used in Sweden [49]. No procedure has been found in the literature to calculate the capacity of the energy storage necessary to supply the national power grid in the event of the disappearance of electricity production from RES. The value obtained above seems very small. It seems impossible to build an energy storage at such a low price.

Unfortunately, these prices cannot be compared to the retail prices of supercapacitors in any way. In the case of the discussed energy storage, there is a large-scale effect. In addition, the operating costs of the nuclear power plant and the solar farm should be taken into account. Moreover, taking into account the currently difficult geopolitical situation and the turbulence on the market for currencies and electronic components, it is difficult to calculate the true cost of building an energy storage facility capable of powering the entire country.

7. Conclusions

The process of decarbonization is a complex endeavor that varies from one country to another. Poland, still devoid of nuclear power plants and predominantly reliant on coal power generation, faces unique challenges. The establishment of new nuclear facilities is a costly proposition, and there is a compelling case to avoid replacing all retiring coal plants with nuclear ones.

The decarbonization requires an increase in the use of renewable energy sources in the energy market. This, in turn, requires many new high-capacity energy storages. The decarbonization process is not the same in all countries. Poland does not have any nuclear power plants so far, and its energy market is based on coal power plants. Building new nuclear power plants is very expensive. In the case of countries with a similar energy market as Poland, there is no need to replace all current coal-fired power plants with nuclear power plants. In order for electricity production to remain at the current level after the closure of coal-fired power plants, it seems necessary to build five to six nuclear power plants in Poland. However, the above considerations show that it is possible to stick to building only one or two nuclear power plants. In that case, the remaining part of the needed energy would be generated by wind and solar farms (there is no possibility of building large hydroelectric power plants in Poland and in most Central European countries). The presented paper proposes the following structure of the electricity energy market (mix): nuclear power plants 20% and RES 80%. The results of the analyses and calculations showed that the electricity energy storage in Poland should have a capacity of 5.43 TWh. Financial resources allocated for the construction of the remaining nuclear power plants could be invested in a new type of energy storage based on a supercapacitor. This will allow for a radical increase in the share of renewable energy sources in Poland's energy market. Supercapacitors are a new solution that is competitive with batteries in stationary energy storage. The main advantage of supercapacitors is their longer service life compared with batteries. Estimated calculations indicate that the investment in energy storage will be competitive to the construction of a nuclear power plant if the unit cost of energy storage is lower than 0.018 USD/Wh for an energy storage capable of powering the entire country for a week (with no electricity produced during that time).

The use of rechargeable batteries is not beneficial for decarbonization because their lifetime is not long, and their production requires the emission of significant amounts of CO_2. An advantageous solution is the use of supercapacitors that are suitable for energy storage. In the coming years, most of the coal mines in Poland will be closed. In these locations, large energy storage facilities based on supercapacitors could be built. The above results for Poland in the presented paper constitute a starting point for conducting further research for other countries. The presented analysis of the possibility of using SCs with an 80% share of RES in the energy market is not universal for all regions in the world—different locations of the world experience different climatic and weather conditions. The results of similar studies for other regions of the world will be presented in the next paper.

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