Future Polish Zero-Carbon Energy Mix Combining Renewable and Nuclear Energy Sources

Maciej Lipka[1]

Abstract

Poland, like other countries, must carry out an energy transition in the coming years. Its goal is to participate in global efforts to stop climate catastrophe by reducing anthropogenic greenhouse gas emissions to achieve net-zero emissions. Energy transition, meaning departure from fossil fuels, mainly hard coal, lignite and fossil gas, requires using the full portfolio of low-emission sources: nuclear, wind, solar, biomethane, and other available low-carbon sources. The analysis demonstrates Poland's optimal zero-emission energy mix and its comparison with the current fossil-dependent mix, determined from the point of view of the reliability of electricity supply and minimization of its carbon footprint. For this purpose, actual data on the availability of renewable energy in Poland and data from the Polish power system were used, and with Monte Carlo modelling, the final energy mix was selected. It is presented and compared with the theoretical renewable-only alternative mix.

Keywords Energy transition · Nuclear · Renewable · Poland · Net-zero

1 Introduction

Like other countries, Poland must carry out an energy transition in the coming years. Its goal is to participate in global efforts to stop climate catastrophe by reducing anthropogenic greenhouse gas emissions to achieve net-zero emissions. Energy transition, meaning departure from fossil fuels—not only coal but also natural gas, requires using the full spectrum of low-emission sources: nuclear, wind, solar and biomethane, and other available low-carbon sources. Nowadays, due to the Russian invasion of Ukraine and an increase in fossil fuel prices that followed it, departing fossil fuels is not only a climate but also a strategic necessity.

There is extensive literature on the energy transition, both at global and regional levels. The authors share commitment to advancing our understanding of energy systems, driving the transition to sustainable and renewable energy sources, and addressing the complex challenges related to energy modelling, market dynamics, policy, and technological innovation. Fodstad et al. [1] summarize the challenges of energy modelling, especially cross section interdependences among energy sources. Fatahi et al. [2] support those claims on the basis of the literature review focusing on nineteen integrated energy system models and recommend combining various levels of modelling. In some studies, authors claim that on global scale, renewable energy, i.e. wind and photovoltaics will be dominant [3–5]. However, articles covering regional level or state level energy transition point out that the most important thing for the success of the energy transformation is to take into account local weather, climate and energy conditions. Notable examples of those are Abdussami et al. [6] and Shen et al. [7]. Similar conclusions come from the studies concentrated on Europe by Janota et al. [8] and Prina et al. [9]. When the Poland's future energy mix is modelled, authors usually claim that in Polish conditions combining nuclear and renewable energy sources makes energy transition easier, and however, they need to be supplemented by energy storage and gas capacities [10]. Authors agree with their peers from different regions that the full portfolio of energy sources is needed, especially Antosiewicz et al. [11] noted that 'absence of nuclear power in the decarbonization pathway may lead to power shortages'. This paper draws on the above-mentioned experiences, taking into account the regional conditions and geographical location of Poland. The proposed energy mix

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is similar to that proposed in government documents, but its implementation horizon is further than that provided for in the current Polish energy strategy. This paper is compiled of five sections. An introduction appears before this point, while four sections follow. Section 2 provides a review of Poland's current electricity mix and regional conditions regarding net-zero transition. Section 3 focuses on data and methods used during modelling. A numerical analysis of the hypothetical power system in Poland. The work combines hourly capacity factors of the renewable energy sources in Poland with Monte Carlo sampling, which enabled the selection of the optimal electricity mix. Section 4 presents the results, and Sect. 5 concludes with a discussion of the key findings of the paper.

The analysis presented in this paper demonstrates Poland's optimal zero-emission energy mix, determined from the point of view of the reliability of electricity supply and minimization of its carbon footprint. The system is mapped for the hypothetical year 2049. For modelling, actual data on the availability of renewable energy in Poland and data from the Polish power system were used. As indicated above, scientific studies on modelling the future Polish energy mix are limited, and therefore, current article fills existing research gap.

2 Poland's Current Electricity mix and Regional Conditions Regarding Net-Zero Transition

The current composition of the Polish electricity mix reflects a heavy reliance on fossil fuels, particularly hard coal and lignite. According to recent data in 2022, coal-fired power plants constitute approximately 50% of the total installed capacity, with hard coal accounting for around 43% and lignite contributing around 27% electricity generation [12], the mix is presented in Fig. 1. This dependence on coal has significant environmental implications, as coal combustion is a major source of greenhouse gas emissions, therefore Polish power sector generates about 40% of Polish greenhouse-gases emissions [13] with the average emissivity of 708 kg_{CO2}/kWh [14]. Despite efforts to diversify the energy mix and increase renewable energy deployment, the extensive utilization of fossil fuels in Poland's electricity sector poses challenges for achieving sustainable and climate-friendly energy systems. Transitioning to cleaner and renewable energy sources remains a crucial task for Poland's energy policy.

In Polish conditions, due to the lack of potential for hydropower and high-temperature geothermal development [15, 16], development of other zero-emission power generating resources is needed. These include the sun, wind (onshore and offshore), nuclear energy and a certain amount of sustainably obtained biomethane and biomass [17]. The energy

transition is a challenge. A high standard of living, i.e. citizens' access to public services such as efficient health care, convenient public transport or an efficient state, requires an uninterrupted power supply and, thus, the ability to adjust electricity production to the temporary demand for it, regardless of the weather and the time of day or night.

The energy demand is characterized by high daily and seasonal variability. Traditionally, power plants were divided into baseload, intermediate and peak units [18]. Baseload units worked continuously, only slightly changing its production, intermediate units were launched when the first could not cover the electricity demand, and peak units were turned on only during load peaks. However, as energy systems increasingly incorporate variable energy sources like wind and solar, a new classification is being suggested [19]:

1. Variable sources that save fuel. In Polish conditions, these include weather-dependent renewable energy sources (RES): wind and solar energy, which generate clean energy, but in quantities depending on the weather and time of day.
2. A flexible base or 'Firm' low carbon-resources, i.e. controllable sources generating emission-free energy regardless of the weather, thus supporting uncontrollable, renewable energy sources.
3. Very flexible, 'fast burst' balancing sources used in periods of scarcity, when energy generation is limited due to the resources of the fuel used (e.g. biomethane obtained sustainably) or other conditions related to their availability (e.g. pump). To a limited extent, this function can also be performed by a temporary reduction of demand for energy (demand side response—DSR).

Using all the above types of energy sources is one of the conditions for a successful energy transition. On the one hand, it causes its lower cost, especially in areas with limited renewable energy resources; on the other hand, it makes it not scarce during Dunkelflaute, i.e. periods lasting over twenty-four hours when the wind is not blowing, and the sun is not shining at the same time [20]. The monthly number of hours of this phenomenon for selected European countries is shown in Fig. 2, data taken from the ENTSO-E Transparency Platform [21]. Quality of data has not been analysed. In Poland and Europe, Dunkelflaute can last up to 100 h, i.e. 14% of the month. This phenomenon is important from the point of view of the stability of electricity supplies.

Another condition is independence from imports of electricity from abroad, along with the growing share of variable RES in the system throughout the European Union along with the decrease of the installed power in the dispatchable generation. Plans for the Central Europe are presented in Fig. 3.

There will be periods when there will be an excess of energy or its shortage in all countries, which will make it

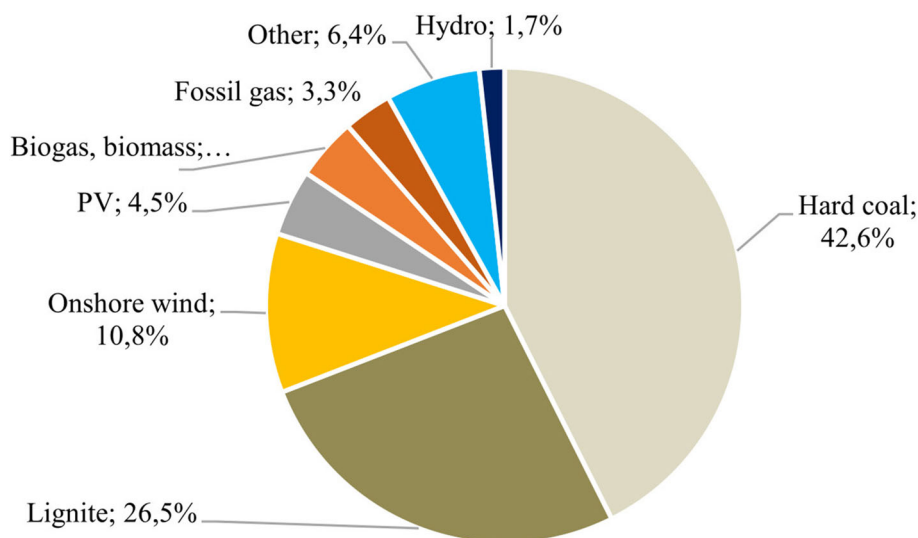**Fig. 1** Current Polish electricity mix in 2022, 175.2 TWh total

Fig. 2 Dunkelflaute—monthly periods of simultaneous wind silence and lack of sun in selected European countries in 2019
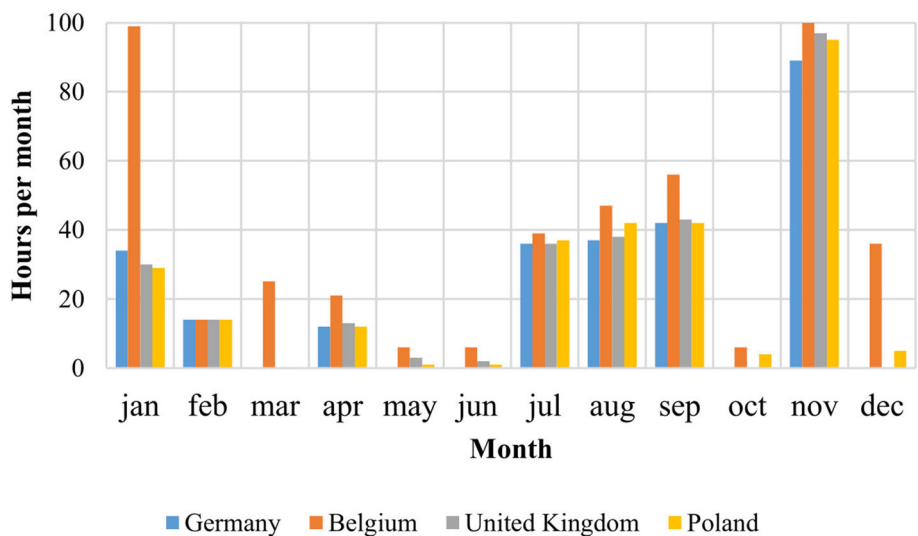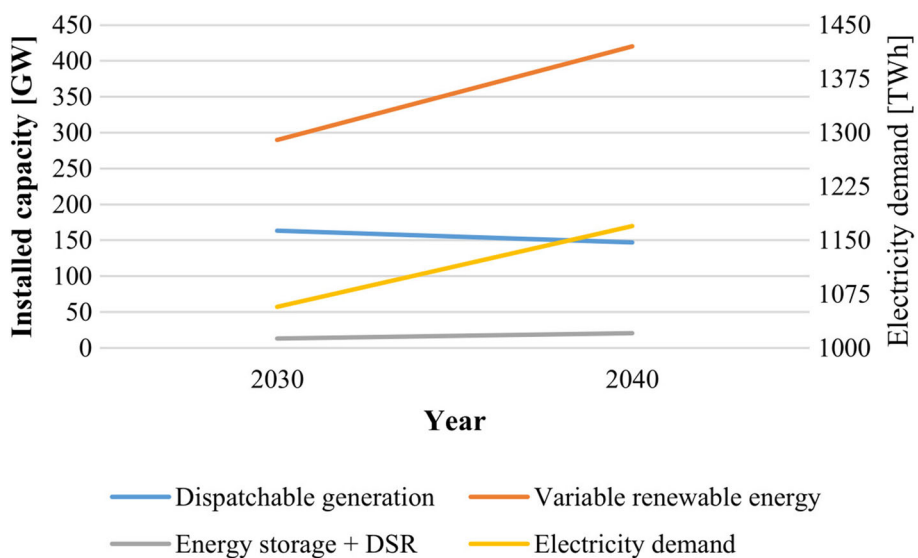

Fig. 3 Trends concerning installed capacity in dispatchable and variable energy generation in Central Europe countries (Germany, Czechia, Lithuania, Poland, Slovakia and Sweden), data from [22, 23]
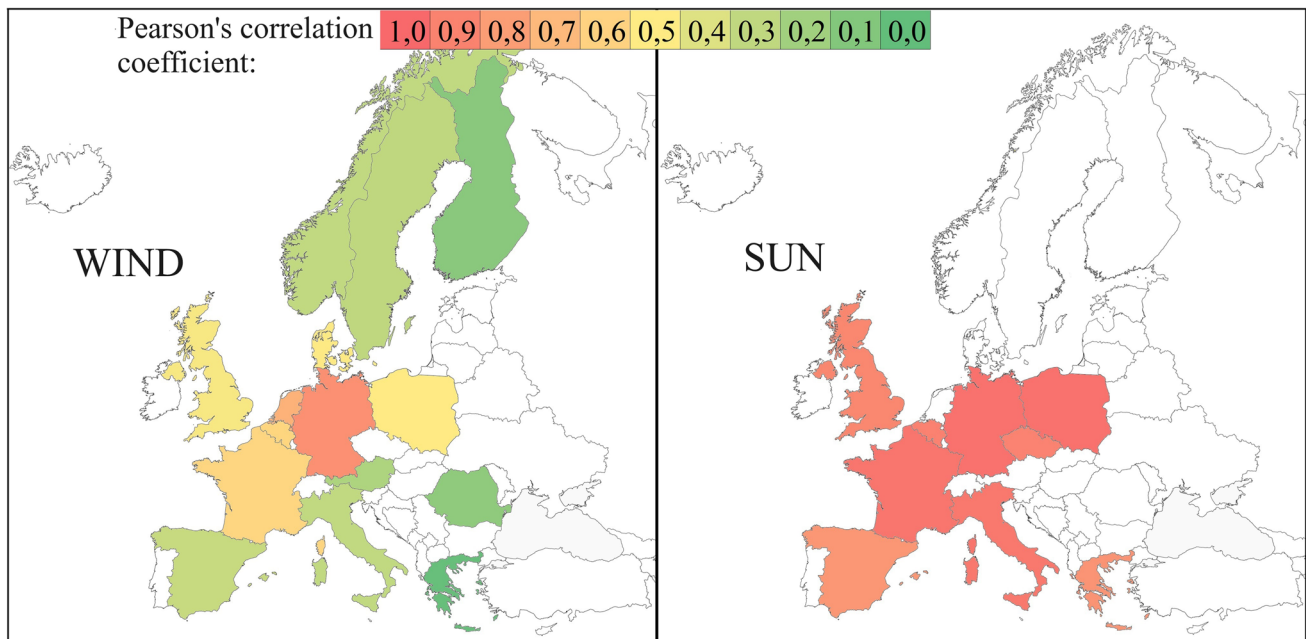
Fig. 4 Pearson correlation coefficient of the simultaneity of a country's wind (left) and solar (right) power generation with the entire area under consideration, 2019

impossible to save oneself with operator interventions consisting of cross-border transmission of electricity on demand. Figure 4 shows the correlation coefficient of electricity generation from wind and solar in European countries against the background of the entire area, i.e. the more red it is, the more renewable sources in a given country work in the same way as in the whole of Europe.

Statistical analysis was performed separately for sun and wind, both according to the Pearson's formula:

$$r_{xy} = \frac{\sum_{i=i}^{8760}(x_i - \overline{x})(y_i - y)}{\sqrt{\sum_{i-1}^{8760}(x_i - \overline{x})^2}\sqrt{\sum_{i-1}^{8760}(y_i - y)^2}} \qquad (1)$$

where i—hour of the year, x_i—instantaneous hourly capacity factor in the hour i, calculated for the whole considered area, y_i—instantaneous hourly capacity factor in the hour i, calculated for the considered country, $\overline{x}$, $\overline{y}$—mean values of x_i and y_i.

Countries with more than 1 GW of installed capacity in the analysed generation source were selected. For wind, Germany dominates, with almost 60% of installed capacity in the area under consideration. Hence, their correlation with the entire area is close to unity. For the sun, the cycle of day and night is dominant. Hence, the entire area works almost the same in time. Additionally, the calculated correlation of the wind and solar power generation for the whole area in hourly resolution in year 2019 equals $r = -0.23$ which is considered weak [24]. The presented data show that weather phenomena behave unexpectedly. There are periods when

energy is in excess (simultaneous generation from wind and sun) and times when it is lacking (simultaneous lack of wind and sun in Europe).

Independence from electricity import, of course, does not mean energy autarchy. However, the only protection against a lack of electricity—cross-border transmission lines should be expanded in such a way as to integrate national networks better, which would enable optimization of balancing demand and supply in European regions, regardless of national borders, which as a rule, optimal area energy systems do not have to coincide with the latter. Of course, this does not mean that integrating national power systems alone is the answer to transition problems.

3 Data and Methods

The model relies on the hourly data of the electricity supply and demand sampled from the ENTSO-E Transparency Platform [21]. The year 2022 has been selected as the basis for the capacity factors calculation as the most recent available. They have been calculated by dividing the electricity generation by the monthly data about the installed power of onshore wind and photovoltaics (PV). As Poland currently does not operate offshore wind farms, data for the German offshore at the Baltic Sea were used (i.e. Arkona, Wikinger, EnBW Baltic 1 & 2 [25–28]) due to their geographical proximity to the Polish territory. The annual electricity demand has been

Fig. 5 Anticipated increase of the Polish annual electricity demand, consumption anticipated as an simulation's input (250 TWh/year) has been indicated with arrow. Data from [21, 29–32]. *IAEA* International Atomic Energy Agency, *PSE* Polskie Sieci Energetyczne (electricity transmission system operator in Poland), *CAKE KOBIZE* Centre for Climate and Energy Analyses of the National Centre for Emissions Management, *PEP2040* Poland's Energy Policy until 2040, *PEP2050* Poland's Energy Policy until 2050. *Note*: PEP2040 is a newer document than PEP2050, which never entered into force
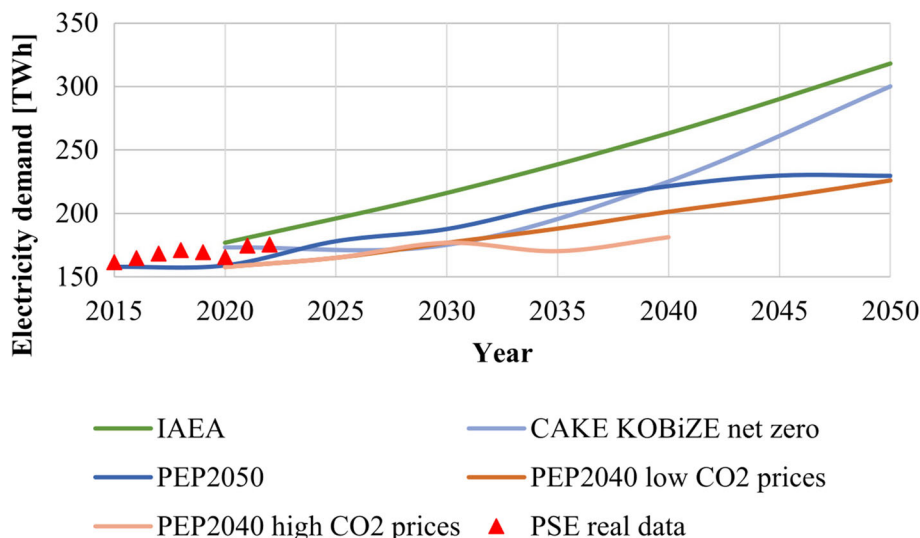
set to 250 TWh as the mean value from the prognoses presented in Fig. 5. However, it is worth noting that the more ambitious the climate goal, the higher the electricity demand due to the electrification of various branches of the economy, e.g. transport, district heating, carbon-free hydrogen production [23, 29].

The hourly load curve was taken from the 2022 data for Poland [21]. On the generation side, for simplification, it was assumed that the nuclear fleet always operates at 100% installed power, but a fraction of the power units are taken offline every 18 months for refuelling. That generation decrease has been included in the calculation. As Poland currently does not have a nuclear strategy up to the year 2049, it was assumed that the installed capacity (12.1 GWe) will be proportionally higher than that described in Polish Nuclear Power Programme [33], i.e. up to 9 GWe in 2043 or, according to the press information about the new Poland's Energy Policy c.a. 8 GW– in 2040 [31].

Additionally, it was estimated that Poland should possess c.a. 15 GWe 'Fast burst' [19] biomethane or biogas sources, a value which is technically feasible [34]. Moreover, 4.2 GW/27 GWh pumped storage hydropower (PHES) will operate in the system (which is in line with the current national policy [35]) and additionally 7 GW/28 GWh of battery storage (proportional to the EU estimates [36]). The rest of the electricity demand is covered by the demand side response (DSR), which minimization both in means of power and time is the optimization goal (as too large DSR is temporary no more and means energy shortages). The system is accompanied by 1.5 GWe of biomass sources operating constantly and c.a. 900 MWe [37], hydropower plants with real hourly capacity factors.

Geographical and weather limits for the maximum installed capacity of photovoltaics, onshore wind, and offshore wind farms have been applied as their maximum

Table 1 Calculated net-zero electricity mixes for Poland: nuclear and non-nuclear scenario

N_i	Power generation technology	Maximum capacity concerned in the simulation (N_{max})
1	Nuclear [GW(e)]	12.1
2	PV [GW(e)]	80.0
3	Onshore wind [GW(e)]	44.0
4	Offshore wind [GW(e)]	28.0
5	'Fast burst' [GW(e)]	15.0
6	Biomass [GW(e)]	1.5
7	Hydropower [GW(e)]	0.9
8	Energy storage [GW(e)]/GWh	7.0/28.0
9	PHES [GW(e)/GWh]	4.2/27.0

physical amount available in Poland. Appropriate values are presented in Fig. 6. It was also assumed that due to the high capital costs of construction, offshore wind and nuclear compete for the capital necessary for construction in a way, so, in that case, the maximum combined installed capacity of nuclear and offshore wind is capped at 28 GWe, which is maximum for the latter in Polish conditions. All of the above-mentioned maximum installed power capacities are presented together in Table 1.

Values from Table 1 served as the boundary conditions (limits) for the Monte Carlo analysis. Values from each category of generation sources have been randomly sampled. Together they have formed 100,000 random power generation mixes. The procedure for selecting random mixes can

Fig. 6 Maximum possible renewables installed capacity in the Polish conditions, data from [38–40]
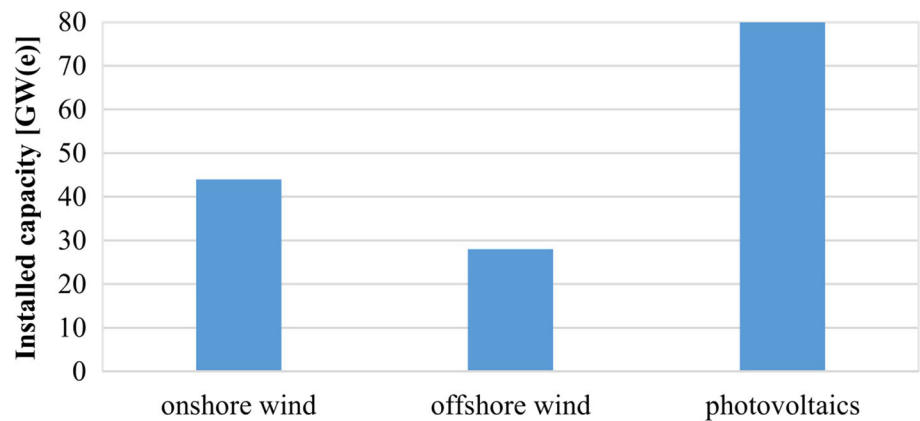
be written as the following formulas:

$$M_n = \sum_{i=1}^{9} N_i \tag{2}$$

$$N_i \in \langle 0, N_{max} \rangle \tag{3}$$

where M_n is random power generation mix, and N_i is installed capacity in one of the technologies listed in Table 1. Separately 100,000 randomly generated mixes without any nuclear power were generated. From each of those set the optimum scenario was selected, those two as named as 'REN-NUC' and 'RENONL' in the next chapter. The criterion for their selection was as few hours of electricity shortage as possible when the given electricity mix is operating in the weather and electricity demand conditions of year 2022, scaled to the demand of 2050 TWh.

Table 2 Calculated net-zero electricity mixes for Poland: nuclear and non-nuclear scenario

	RENNUC	RENONL
Nuclear [GW(e)]	12.1	0.0
PV [GW(e)]	35.0	80.0
Onshore wind [GW(e)]	35.0	44.0
Offshore wind [GW(e)]	15.0	28.0
DSR [GW(e)]/TWh	11.3/1.1	17.2/2.9
'Fast burst' [GW(e)]/TWh	15.0/14.0	15.0/28.5
Biomass [GW(e)]	1.5	1.5
Hydropower [GW(e)]	0.9	0.9
Energy storage [GW(e)]/GWh	7.0/28.0	7.0/28.0
PHES [GW(e)/GWh]	4.2/27.0	4.2/27.0

4 Results

A set of 100,000 simulations with randomly picked installed capacities were run; however, as it was noted, above 10,000, there was no increase in accuracy. Calculations outcome were the two data sets of installed capacities in two scenarios:

- Combining renewable and nuclear power (RENNUC)
- Renewable power only (RENONL)

In the RENONL scenario, the installed capacities of renewables were determined by Monte Carlo to be equal to the actual physical limitations that can be seen in Fig. 6. REN-NUC determined them by the same method but happened to be much lower.

Both scenarios are presented in Table 2, together with the energy volumes required in 'Fast burst' sources and DSR. As can be seen, installed power in the RENNUC scenario is 30% lower. Additionally, 25% of power in DSR is needed.

From the point of view of energy supply and consumption, the nuclear scenario needs 63% less DSR and 50% of the gas amount.

In both scenarios, part of the energy generated is inevitably wasted due to the impossibility of its storage. However, in the nuclear scenario, the losses are 33% lower than in the non-nuclear scenario (66 vs 100 TWh) due to the lower installed capacity in the intermittent renewable sources.

Both the system, its load and electricity sources are presented in the daily resolution in Figs. 7 and 8. Drops in the nuclear generation visible in Fig. 3 are due to the periodic refuelling of the reactors in the modern, 18-month fuel cycle—the procedure partially occurs in spring and partially in summer due to the availability of intermittent solar and wind sources in those periods.

Operation of the PHES, electricity storage, 'fast burst' and DSR in both scenarios are presented in Figs. 9 and 10. Negative values associated with the loading of the energy storage sources were omitted.

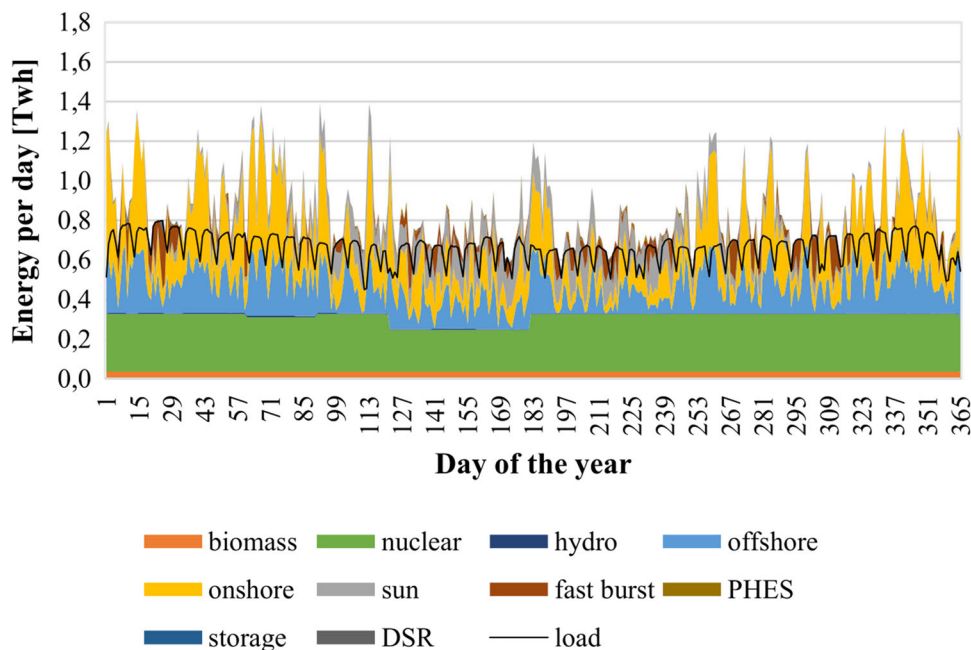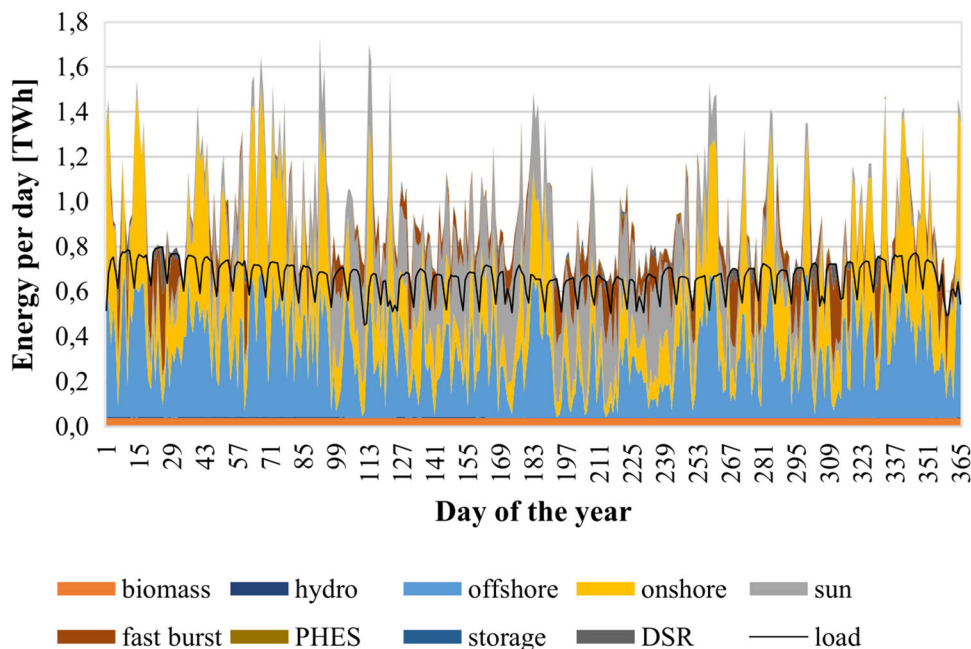**Fig. 7** RENNUC electricity mix in daily resolution

Fig. 8 RENONL electricity mix in daily resolution

DSR and fast burst performance have been visualized below. In Fig. 11, the hourly needs of DSR in both scenarios are presented in an ordered manner. As can be seen, the RENNUC scenario requires about 33% hours of energy savings and lower DSR capacity. Figure 12 presents the ordered manner of hourly gas power required in the two scenarios, as it can be seen that the RENNUC needs are decreasing faster, i.e. smaller back-up is required for the intermitted sources. In absolute terms, the energy stored in biomethane required in the 'fast burst' sources is c.a. 100% higher in the RENONL

scenario. Figure 13 presents electricity generation by all of the sources.

5 Conclusions

The article compares two scenarios, determined by Monte Carlo modelling: cooperating nuclear and renewables, and renewables only. It has been determined that adding nuclear to the portfolio of clean energy sources limits the installed capacity and energy shortages. The following research steps

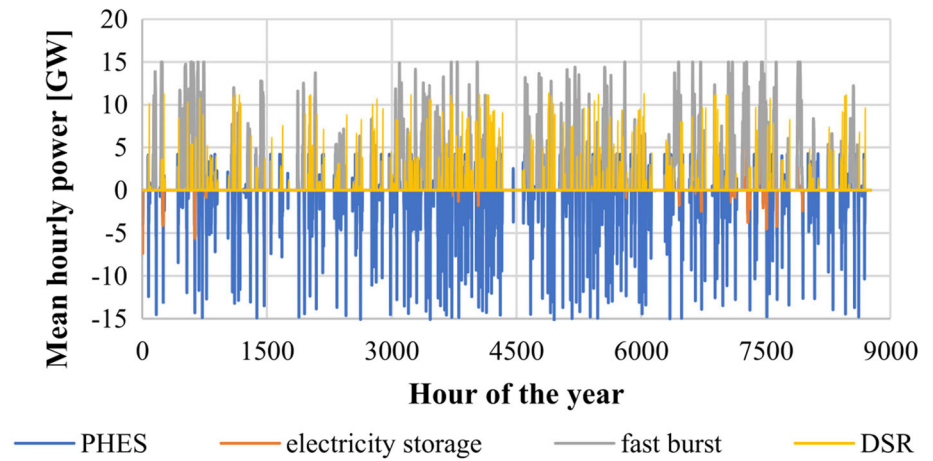**Fig. 9** PHES, electricity storage, fast burst and DSR operation in RENNUC scenario

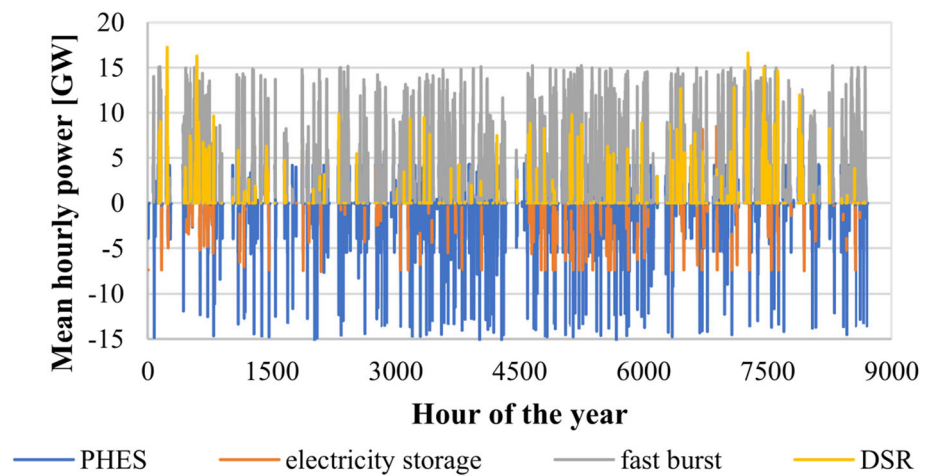**Fig. 10** PHES, electricity storage, fast burst and DSR operation in RENONL scenario
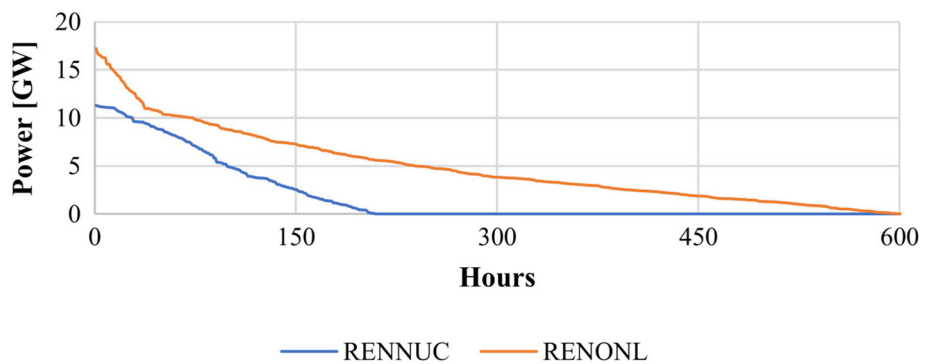

Fig. 11 Ordered line graph of DSR needs in both scenarios

shall involve optimizing the order in which the reserve sources (DSR, PHES, electricity storage and fast burst) join the system. Additionally, the load following of nuclear power plants is going to be considered. The calculated energy mix reduces greenhouse gases emissions from power sector from 708 to 24 g CO_2/kWh, while covering the almost twofold increase in electricity demand that is expected in 2049.

Moving away from fossil fuels is a necessity both because of the spectre of climate catastrophe and Poland's growing dependence on their imports. At the same time, it is a civilizational challenge to carry out the energy transition in such a way as to ensure a stable and reliable supply of electricity at reasonable prices. In every place on Earth, the circumstances will dictate the measures to achieve the goal.

Calculations presented in this article revealed that adding nuclear to the portfolio of technical means will make the net-zero transition way more manageable than in the case without it. Net-zero must be based on renewable energy sources and large, proven nuclear units in Polish conditions. Additional

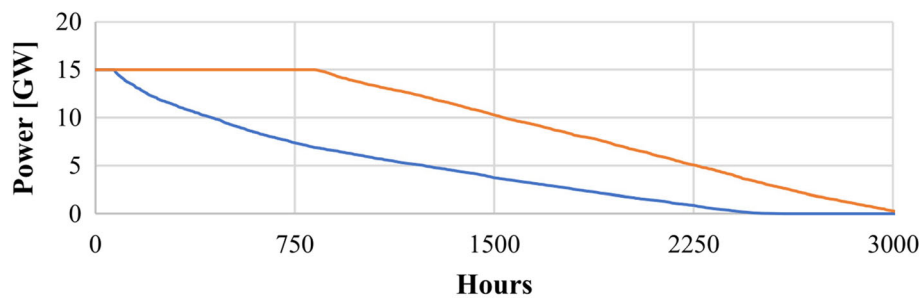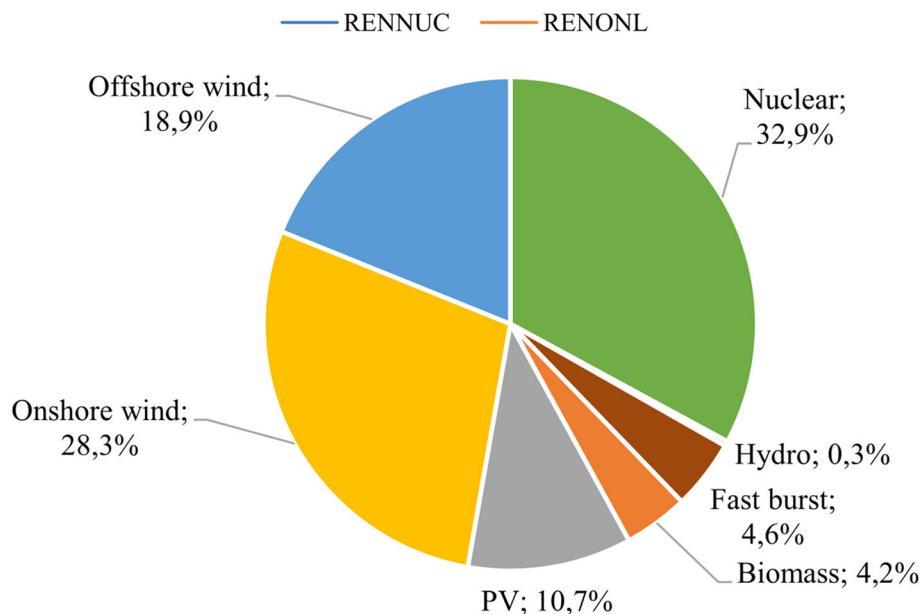**Fig. 12** Ordered line graph of 'fast burst' needs in both scenarios

Fig. 13 RENNUC electricity mix energy generation, 307 TWh total

pieces of the puzzle necessary for success are pumped storage power plants and other types of energy storage, as well as zero-emission peaking power plants, such as those using sustainably sourced biomethane. If any puzzle pieces fall out of the solution pool, the transition will fail, resulting in electricity shortages.

The author envisages further development of his computational model. The changes will include modelling not only based on system data from ENTSO-E, but also the incorporation of weather data. This will make it possible to model the operation of new wind turbines, replacing those currently used. It is also planned to add the possibility of nuclear power operating in load-following mode. All of this will increase the accuracy of the initial model described in this article.

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