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Research article

Investigating the role of nuclear power and battery storage in Hungary's energy transition using hourly resolution electricity market simulations

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ABSTRACT

Electricity supply in European countries faces a number of challenges, such as achieving carbon neutrality, tackling rising prices, reducing dependence on fossil fuels, including fossil fuel imports. To achieve these goals, the electricity systems of all European countries will have to undergo major changes, while taking into account technical, environmental, economic and social objectives. Our simulations provide essential data for this transition by analyzing different power plant portfolios and electricity consumption scenarios. The analyses focus on the cooperation of nuclear power and weather-dependent renewables, and on the possible role that battery-based electricity storage can play in the Hungarian electricity system.

In this paper, we present the experience gained in setting up an electricity market model and the results of running the model on the electricity systems of Hungary and its six neighboring countries (Slovakia, Romania, Serbia, Croatia, Slovenia and Austria), taking into account the constraints of the cross-border capacities. The results of the sensitivity analysis for the 2030 power plant portfolios, battery capacities and renewables analyzed in this paper cover Hungary's import/export position, the energy source structure of its electricity generation, battery operation, CO2 emissions from electricity generation, expected prices in the system and the utilization parameters of nuclear power plants.

1. Introduction

The energy supply faces many challenges in the short and long term. The main aspects of these challenges are tackling climate change, achieving sustainability, while ensuring affordable and secure energy supply. The European Union has set a target for the decarbonization of the energy sector under the European Green Deal [1], which means that countries' electricity systems should be net zero carbon by 2050 [2].

To achieve the decarbonization targets, the electricity system in European countries will have to undergo significant changes, taking into account technical, environmental, economic and social aspects. The path to achieving the targets will be further complicated by the ongoing Russian-Ukrainian war, which has led to a rise in energy prices and has led European countries to set themselves the objective of reducing their dependence on Russian fossil energy imports. Taking all these factors into account, it can be

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concluded that the most important task for European countries is to replace fossil fuels, reduce Russian energy source imports and keep prices at affordable levels.

According to the analysis of several authors, such as Buongiorno et al. [3], Dincer et al. [4] and the ENTSO-E and ENTSOG joint report [5], renewable energy, nuclear energy, grid-scale electricity storage and hydrogen technology can play a major role in this challenge. However, these technologies are either still in the demonstration phase (grid-scale battery based storage, hydrogen) or there is little data on their stable and sustainable cooperation (e.g. weather-dependent renewables and nuclear power), so a detailed technical, economic and environmental analysis of the systems composed of these technologies is essential.

In order to achieve decarbonization targets, the European Union has required member states to prepare a National Energy and Climate Plan (NECP) [6], which outlines the country's path towards a net zero-emission energy system. Following the publication of each country's plan, a number of studies have been carried out to analyses them. Simoglou and Biskas [7], for example, evaluate the Greek NECP and demonstrates that the plan to phase out lignite and deploy renewables on a large scale will lead to a gradual but radical transformation of the energy mix, in which pumped-storage hydro power plants are expected to play a key role in mitigating the negative effects of intermittent renewable generation. Williges and colleagues [8] point out that the implementation of NECPs may lead to underestimation of impacts, failure to reduce greenhouse gas emissions or increased resistance to climate policies due to neglecting key aspects ("efficiency, effectiveness and feasibility").

The role of nuclear energy in the decarbonization process has been the subject of several recent studies. Kindi and colleagues [9] have shown that linking nuclear power plants to thermal energy storage could ensure the continued operation of nuclear power plants and make their operation more flexible. Duan et al. in a similar paper [10] concluded that in a highly decarbonized system, nuclear power will be economically viable in countries with low wind energy potential (Hungary is one of these countries). In his study [11], Cepin demonstrated that replacing a nuclear power plant with wind power plants of five times the nuclear capacity causes a reduction in the reliability of the electricity system. The above articles demonstrate that, despite the energy policy debates, nuclear power has important role to play in future low-emission electricity systems, and that it is essential to examine their effective cooperation with renewable energy sources.

Beyond nuclear energy, grid-scale energy storage will also play a significant role in achieving net-zero emission electricity systems. There are a number of technologies for energy storage [12], of which battery storage has been playing an increasingly important role in recent years. However, most of the research on these storage systems [13,14] approaches the issue from a capacity expansion perspective rather than from the point of view of the market behavior of batteries at hourly resolution. Those that focus on the latter have concluded that short-term electricity storage can provide cheap and fast energy supplies to compensate daily fluctuations [15, 16].

In our previous study [17], detailed power system models were developed at the Budapest University of Technology and Economics to analyze the future (2030, 2040) power system of 19 European countries using the Energy Scenarios Simulation Tool (ESST) developed by the International Atomic Energy Agency. The study has shown that the reference day modelling approaches used for the development of the National Energy and Climate Plans of the individual governments cannot describe the electricity system with sufficient accuracy, and that system modelling with at least hourly resolution is essential for the development of appropriate strategies and the analysis of impacts and consequences. The model used in the study is capable of hourly-resolution simulations, taking into account the hourly pattern of consumption and renewable generation, but this modelling environment is not able to model the more subtle technical characteristics and constraints that affect cross-border capacity, electricity storage and other factors that limit the electricity generation of different power plants. Based on the lessons learned from the previous study, we concluded that more sophisticated electricity market models should be used to model low-carbon electricity systems at the appropriate level, for which purpose we chose the Energy Exemplar's PLEXOS [18] code.

The main topic of this paper is the modelling of the Hungarian electricity system together with its neighbors, so it is important to review the literature on this topic. Kiss et al. [19] have performed hourly resolution simulations of the Hungarian electricity system using EnergyPRO [20] software, which was used to study 3 power plant portfolios. Their results show that the portfolio chosen by the authors would have a higher fuel diversification, a higher share of renewables, lower emissions, but much higher costs. Campos et al. [21] built 2033 models of the Hungarian electricity system using EnergyPLAN software and examined the compatibility of wind and solar with projections of future electricity demand in Hungary, and estimated the excess generation. In their study, they found that 46 % of electricity consumption could be produced by wind and solar PV technology, with less than 5 % of annual overproduction. It should be noted that the models presented in the [19,21] studies are not able to model the detailed technological parameters of cross-border capacities and neighboring countries, power plants, and the hourly inputs of renewable energy sources are only based on a few years of data, so it can be stated that the model presented in this study has a much higher resolution and gives a much more detailed picture of the possible future of Hungary's electricity system compared to these models.

Based on the literature study, it can be concluded that our present paper is the first to model the combined electricity system of Hungary and its neighboring countries with a high time resolution, describing the elements of the electricity system in great detail, and to use the model to assess the situation of nuclear, renewables and grid-scale battery storage in the Hungarian electricity system. The main contribution of the research presented in this paper to the results in the literature in this field is as follows:

- a model is proposed for the Hungarian and neighboring countries' electricity systems in year 2030 in the PLEXOS to perform hourly resolution simulations,
- guidance and extensive literature study is provided on the technical and economic parameters of power plants and electricity storage units,
- results of the impact of new nuclear units are given,

- probabilistic sensitivity analysis of the impact of weather dependence of renewable energy sources is shown on the Hungarian electricity system,
- scenario-based analysis of the capacity of the Hungarian battery fleet is provided.

Section 2 of the paper presents the data and methods used in the research, Section 3 provides the results of the simulations, while Section 4 summarizes the results and draws conclusions from the analysis. In Appendix A of the article, data for the modelled countries are given, Appendix B describes the technical and economic parameters of the power plants, while Appendix C presents additional figures on the state of charge, charging and discharging patterns of the batteries planned for the Hungarian electricity system.

2. Data and methods

The purpose of modelling the electricity system at hourly resolution is to describe, for each hour, how demand can be met at the lowest cost, using which plants, in relation to demand, available plants and variable costs, so that production is in balance with consumption. This task must be carried out while optimizing the total operational cost of the system and taking into account the operating constraints of the individual elements that constitute the system. To perform these tasks in this work, we have chosen the electricity market modelling software PLEXOS [18] from Energy Exemplar. The PLEXOS software is widely used in electricity market research, with applications ranging from the detection of errors in low time resolution models [22], to the creation and validation of global electricity market models [23], to analysing the impact of wind power on the transmission grid [24], to the study of the operational requirements of gas power plants [25].

2.1. Introduction to the PLEXOS modelling environment

PLEXOS is a deterministic mixed integer optimization model that minimizes the expected cost of electricity generation, taking into account various parameters (efficiency, minimum stable generation, ramp-up/down rates, etc.) [26]. PLEXOS performs electricity market optimization along 4 different time horizons and objectives, which are described in the PLEXOS User Guide as follows:

- Long term (LT) plan: At this stage, the software looks for the optimal combination of building new plants and decommissioning existing plants, as well as building and decommissioning transmission lines, while minimizing the net present value (NPV) of the total system costs over a long-term planning horizon.
- Projected Assessment of System Adequacy (PASA): This section of the software is used to model the maintenance and unexpected outages of power system components.
- Medium term (MT) schedule: MT Schedule's objective is to optimize medium to long term decisions in a computationally efficient manner. Primarily this means managing hydro storages, fuel supply and emission constraints, but there are many other constraints and commercial considerations that need to be addressed over timescales longer than a day or week.
- Short term (ST) schedule: ST Schedule is mixed-integer programming (MIP) based chronological optimization. It is designed to emulate the dispatch and pricing of real market-clearing engines, but it provides a wealth of additional functionality to deal with: unit commitment, constraint modelling, financial/portfolio optimization, Monte Carlo simulation, stochastic optimization.

To perform the optimization of the system, ST optimization must be performed, and LT, PASA, and MT are optional. Within the scope of this research, ST optimization was performed in PLEXOS.

The temporal resolution of the model can range from user-defined intervals of 1 min to intervals of several hours. Within the framework of this research, a model has been built in the PLEXOS environment in which the electricity system of the countries under study is represented by a single node. The transmission network within countries was not modelled within the scope of this research. The cross-border capacities between countries are represented in the model by one cross-border interconnector per country pair.

The built model has a time horizon of 1 year and a resolution of 1 h. The software solves the problems with hourly resolution in 1-day steps, so that the optimization takes into account the 24 h of the current day. The country and technology specific data fed into the model are presented in the following sections. The model does not take into account plant maintenance and outages that are not expected, as the necessary data were not available.

2.2. Data for the modelled countries

Government plans for the future of a country's electricity system are foreseen in the country's National Energy and Climate Plan (NECP), so we have used these documents to build the models.

We looked at Hungary and its immediate neighbors. The future of electricity generation in Ukraine has become unpredictable due to the current war situation, so Ukraine was not modelled in this study. In addition to Hungary (HU), Romania (RO), Serbia (RS), Croatia (HR), Slovenia (SI), Austria (AT) and Slovakia (SK) were included in the model.

2.2.1. Demand data

One of the most important factors in a country's electricity supply is the annual consumption of electricity and its hourly pattern. Of the countries studied, Austria [27], Hungary [28] and Slovakia [29] have provided in the NECP an exact value for the country's expected electricity consumption in 2030. In the case of Romania [30] and Slovenia [31], we were able to calculate an increase between 2019 and 2030 consumption based on the data provided in the NECP. For Croatia, only the share of renewables in electricity production and the amount of electricity produced by each renewable energy source in 2030 were included in the NECP [32], so we could estimate the 2030 consumption based on these data. As Serbia is not a member of the EU, it has not been obligated to prepare a NECP so far. Nevertheless, according to official communications, Serbia intended to have such a document by the end of 2022, but at the time of modelling and writing the study (during 2023), this document was not yet available. Although a preliminary draft of it is available [33], it does not contain any data on the country's electricity consumption projections, so for Serbia we have defined the 2030 consumption based on [34]. The annual consumption values defined for each country in the model are presented in Appendix A, Table 2.

To determine the hourly profile of consumption, the data for 2019 for neighboring countries were downloaded from the website of the European Network of Transmission System Operators for Electricity (ENTSO-E) [35], and the Hungarian data from the website of the Hungarian Electricity Transmission System Operator (TSO), called MAVIR Zrt [36]. The methodology used for data extraction was described in our previous article [37].

We had to check the quality of the downloaded data sets and correct the values of those meters where, due to some error, there was no value for the consumption of the given hour in the public database. These incorrect values were replaced by the average of the consumption before and after the given hour (2 such data in the Slovak and 1 in the Romanian dataset).

As the data available in the ENTSO-E database on the electricity system in Austria are at quarter-hourly resolution, the Austrian dataset has been converted from quarter-hourly to hourly resolution. The hourly resolution electricity demand data for 2030 were obtained by multiplying the hourly system load derived from the evaluated hourly system load data series for 2019 by the ratio of the estimated annual consumption in NECP for 2030 to the annual consumption in 2019, using the approximation that the hourly profile of the consumption in 2030 will be the same as the hourly profile of the consumption in 2019.

A more accurate estimate could only be made if we had detailed projections of weather data for 2030 and the impact of economic growth and electrification on hourly consumption, but these data were not available at the time of writing this paper and this research was not intended to produce such a dataset. In a previous paper [37], we developed a neural network-based methodology that can generate hourly-resolution consumption and renewable energy production data series based on 42 years of hourly-resolution meteorological data. These synthetic datasets could be a suitable input for such electricity market research. However, based on this methodology, we have so far only been able to produce synthetic data for Hungary, not yet for neighboring countries, so in the present research these data were not used as hourly consumption input for the models.

In the present research, a sensitivity analysis was carried out to investigate the impact of weather-dependent power generation, in the framework of which the hourly resolution capacity factors of solar and wind power plants were defined in the model not only on the basis of data for 1 year (2019), but also on the basis of data for 40 different years (1980–2019) (for more details, see Appendix B Section B2). Within the sensitivity analysis, we had to modify the consumption and hydropower data series to include leap years, which are described in detail in Appendix A.

2.2.2. *Installed capacity*

As with the consumption values, the installed capacities are based on the NECP documents. Since the NECPs only provide installed capacities at the energy source level, not at the power plant unit level, we used only energy source level resolution in the model to define the electricity sources. On the generation side, we distinguished 14 different power plants and assigned to them the capacities presented in the NECP documents. The modelled units can be classified into the following types: nuclear power plant, coal-fired power plant, natural gas-fired power plant, oil-fired power plant, run-of-river hydro power plant, reservoir hydro power plant, pumped-storage hydro power plant, wind power plant, solar power plant, geothermal power plant, biomass-fired power plant, waste-fired power plant, biogas-fired power plant and lithium-ion battery power storage.

The NECP documents did not specify hydropower capacities, so no distinction was made between run-of-river, reservoir and pumped-storage hydro power plants. In order to address these shortcomings, the predicted increase in hydropower capacity in the NECPs has been split between run-of-river and reservoir power plants according to the 2019 installed capacity ratio, as pumped-storage plants are not only affected by their installed capacity but also by the size of the water reservoir (see Appendix B in Section B3 for more details), which is also not available in the official documents. Therefore, the installed capacity and reservoir size of pumped-storage hydro power plants are given in the model based on [38]. In the case of Hungary, no reservoir power plant was defined in 2030, the Hungarian run-of-river and reservoir power plants were defined as a single aggregate generator in the model.

Of the countries studied, Croatia, Hungary, Romania and Slovakia provided exact installed capacity values that can be fitted to the model straight away. Slovenia's NECP did not provide detailed information on installed capacity in 2030, only a bar chart of electricity generated from the energy source. From this bar chart, the installed capacity was calculated using the 2017 capacity factor of the power plant using the energy source. For Austria, a similar approach was followed, but using the 2015 capacity factor. For Serbia, the installed capacity of solar and wind power was already given in the preliminary NECP document [33], the capacity of the other energy sources was given based on the [34] document, which was already used previously.

We have also defined 3 portfolios to examine the evolution of Hungarian capacity in 2030. In order to map the impact of the Paks 2 investment, we defined Portfolios 1 and 2 in the model depending on whether the plant is present in the Hungarian electricity system in 2030. In Portfolio 3, we wanted to look at the latest trends [39], so in this Portfolio we have increased Hungary's annual electricity demand – due to the consumption of large battery factories and their service sites in the country –, we have also increased the capacity of natural gas-fired power plants by the capacity of the CCGT power plants planned for the Tisza and Mátra sites, and increased the installed capacity of solar power plants in Hungary, as the rate of increase of installed capacity of solar power plants in Hungary is well above the plans in the Hungarian NECP.

The installed capacities of the energy sources projected in the countries for 2030 and the portfolios defined for Hungary are summarized in Table 2 in Appendix A.

2.2.3. Cross-border capacities

The electricity systems of neighboring countries are linked by cross-border interconnection capacities, which also creates the potential for cross-border electricity trade between the two markets. Cross-border capacities are represented by a single line in the PLEXOS model, where the maximum capacity to transmit electricity in both directions is limited, depending on the aggregate cross-border capacities between countries. The software thus generates cross border flows similar to the real market environment, depending on prices, consumption and production in different markets and the amount of cross border capacity. The values of the cross-border capacities in 2020 and 2030 are summarized in Appendix A, Table 3. In Fig. 1, the nodes of the model built in PLEXOS and the cross-border lines connecting the nodes are shown to facilitate better insight into the physical flows of the model.

2.3. Technical and economic parameters of power plants

The difference between a simple and a complex electricity market model is the accuracy with which it describes the technical and economic characteristics of the power plants in the electricity system. In PLEXOS, many predefined properties can be assigned to a power plant for this purpose, and the technical and economic parameters of the power plants can be modelled with sufficient accuracy by adjusting the parameters. The 14 energy sources we have studied have been categorized according to whether the power plant generates electricity from thermal or renewable energy and pumped-storage power plants and lithium-ion energy storage plants have been separated. The power plants in the different categories are described with different parameters to best reproduce the market behavior of the specific power plant.

The definitions of technical and economic parameters are presented in Appendix B, based on the PLEXOS User's Guide. An extensive literature study was also carried out on the parameters, the results of which are also presented in Appendix B.

We wanted to highlight lithium-ion energy storage units, which were defined only for the Hungarian system, as the other NECPs did not provide exact data for these units. The Hungarian NECP issued in 2020 was the official energy strategy when this research was launched. This document defines the power of the batteries as 100 MW by 2030, but does not define their storage capacity. Therefore, a sensitivity analysis was performed for this value, in which the capacity of the Hungarian battery fleet was tested in 4 different scenarios, namely 1 h (Scenario A), 2 h (Scenario B), 4 h (Scenario C) or 8 h (Scenario D) capacities were given for the 100 MW power battery park.

A new type of capacity factor has been defined to evaluate battery charging and discharging. The classical annual peak capacity factor used for power plants is not appropriate for batteries, as these units cannot release energy every hour because they must be charged before discharging. Taking this into account, we defined the capacity factor for battery energy storage units by taking into account both charging and discharging periods for the charging hours, so that, in the optimal case, they would have an annual total capacity factor of 100 % if the battery was charged at maximum power for half the hours of the year and discharged at maximum power for the other half of the year. This is of course a theoretical maximum, batteries will not be used that much in any market, but the introduction of such a capacity factor makes it easier to assess battery utilization.

For batteries, we have also defined a profit based on the difference between the price of electricity bought and sold, considering the variable costs of operating and maintaining the battery. The profit was then standardized to 1 MWh of electricity discharged, so that different battery scenarios could be compared. The defined specific profit is described in Eq. (1).

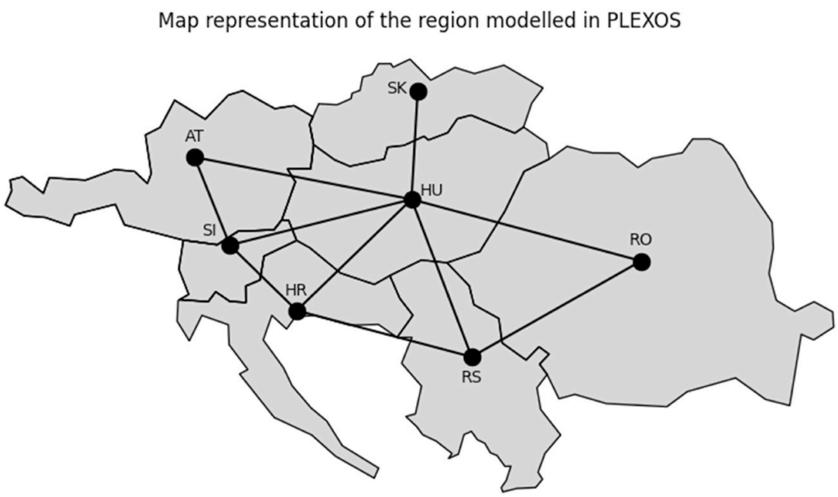

Fig. 1. Visualization of the nodes and cross-border connections of the model built in PLEXOS.

$$c = \frac{(C_{e;s} - VOM) - (C_{e;b} + VOM)}{E} \tag{1}$$

where c is the specific profit of the battery, $C_{e;b}$ is the price of electricity purchased for charging, VOM is the variable operating and maintenance cost of the battery, $C_{e;s}$ is the price of electricity sold at discharge and E is the amount of electricity discharged from the battery.

3. Results and discussion

This Section summarizes the results of the PLEXOS simulations and the conclusions drawn from the results. In this Section, only the values for Hungary are presented, since many other neighbors of neighboring countries – not covered in this research – have not been modelled, so the boundary conditions of neighboring countries are not sufficiently precise to draw far-reaching conclusions from their results. In the case of Hungary, however, all neighbors – except Ukraine – have been modelled, so the results for Hungary are considered as sufficiently accurate. In the future, we also plan to extend the model to a wider area, where we plan to investigate the impact on the Hungarian 2030, 2040 market by modelling not only Hungary and its neighbors, but also the neighbors of the surrounding countries. A complete model would require describing the markets of whole continental Europe, which was above the scope of the actual work, but which is interesting for future works.

The Section covers Hungary's import/export position, the structure of the energy mix of Hungarian electricity generation, the performance of the Hungarian battery fleet, the CO2 emissions of the Hungarian system, the electricity price in the Hungarian system and the capacity factor of the Hungarian nuclear capacity.

A sensitivity analysis was also carried out to determine the uncertainty of the weather-dependent power generators, in which 40 years of solar and wind power capacity factors were defined in the model (explained in detail in Appendix B, Section B2). This sensitivity analysis provides an opportunity to evaluate the model results on a frequency basis and to show the impact of the weather dependence of solar and wind power and the resulting uncertainty on the calculations. Boxplot diagrams have been used to visualize the results, as this representation provides a good visualization of the distributions.

We defined three power plant portfolios depending on the Hungarian power plant capacities and electricity consumption and introduced four different scenarios for the Hungarian battery storage capacity expected in 2030, giving a total of 12 cases for the simulations. To properly identify these cases, we have assigned numbers to the Portfolios (1, 2, 3) and letters to the Scenarios (A, B, C, D). These combinations are also shown in Table 1 and consistently used in the figures below.

In many cases, the results at hourly resolution are graphically represented as a matrix, a so-called "heat map diagram" (see e.g. Fig. 4). This representation was introduced in Ref. [17] to illustrate the large amount of data for a given parameter per year. In these diagrams, we plot a parameter along the y-axis along the hours of the day (1-24) and along the x-axis along the days of the year (1–365), so that the diagram represents all 8760 h of the year. The data for each hour varies according to the color scale defined for the figure. On the y-axis of the graphs, only the names of the months are shown on the first day of each month for ease of understanding.

The average marginal cost for the generators in the system, based on the technical and economic parameters defined and presented in Appendix B, is shown in Fig. 2. The average marginal cost of a power plant is the sum of the fuel cost, the variable O&M cost and the CO2 emission cost (assumed to be the same for all countries, at all hours) and represents the cost at which a plant can increase its production by 1 MWh. These costs will determine the merit order of the electricity market in each country, meaning which generators can enter the market and which cannot, depending on consumption, installed capacity and generation costs in a given hour, and the resulting market price, and the source structure of electricity generation in a given hour.

3.1. Import/export position

A key question in our analysis is whether Hungary's power system can meet the country's electricity needs in 2030 with the planned power plant portfolios, and when the country will be in an import or export position. To illustrate this, we have plotted Hungary's annual import/export position in 2030 for each portfolio and scenario in Fig. 3. The installed capacity data for each power plant portfolio are summarized in Appendix A/Table 2.

The analyses presented here show that Hungary will still be in a net import position in 2030 in all portfolios, but the amount of electricity imports necessary to meet the country's needs varies significantly between portfolios. In Portfolio 1, Hungary imports only around 3.7 TWh of electricity in a year, while in Portfolio 2 the import volume is already 20.6 TWh, which suggests that in case the Paks 2 nuclear power plant with its installed capacity of 2400 MW does not produce electricity for the grid in 2030, the country's power system will only be able to replace the lost electricity from foreign sources. Portfolio 3 should be compared with Portfolio 1,

Table 1
Labels for the defined plant portfolios and battery scenarios.

		Battery capacity scenarios			
		A (1h)	B (2h)	C (4h)	D (8h)
Power plant portfolios	**1** (New nuclear)	1A	1B	1C	1D
	2 (BAU)	2A	2B	2C	2D
	3 (Recent trends)	3A	3B	3C	3D

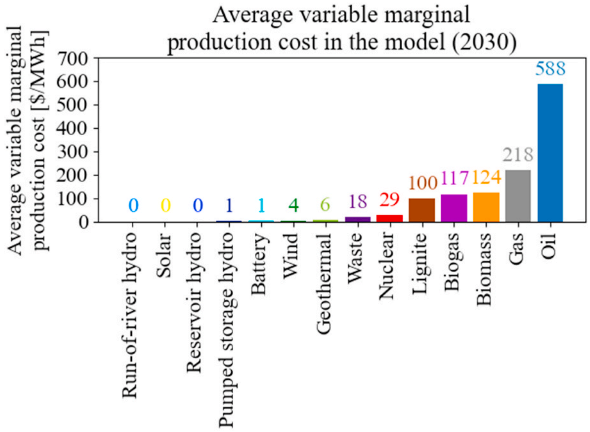

Fig. 2. Average marginal cost of energy sources in 2030.

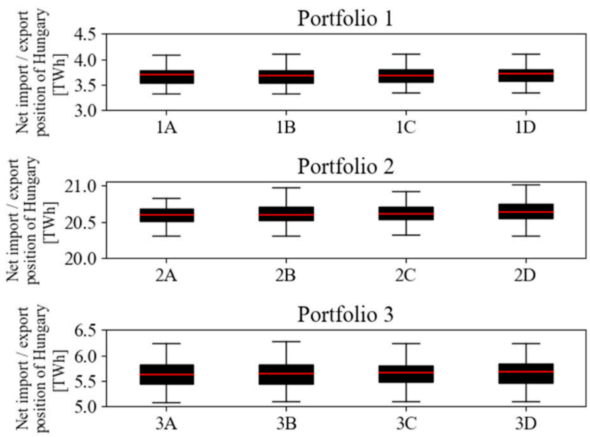

Fig. 3. Evolution of Hungary's net import/export position in three different power plant portfolios and four different battery scenarios.

which shows that the increased consumption cannot be fully met by new solar and gas power plants, as the country's net import position increases by 2 TWh between the two portfolios.

It is important to observe the effect of weather-dependent renewables: the uncertainty bands in the boxplot diagrams in Fig. 3 clearly show that there can be a difference of up to 1 TWh in the country's electricity trading position between years depending on the weather, which is a significant variation. For the battery scenarios (A, B, C and D), it can be said that due to the small total capacity of the batteries, the impact of the batteries on the country level data is very low. Consequently, only in Section 3.3, which deals specifically with batteries, we have shown the battery development scenarios separately, and in all other Sections data for Scenario B are shown, because, in consultation with industry experts, Hungarian energy companies are most likely to invest in 2-h batteries, and government incentives also point in this direction.

In addition to the annual import/export positions, we also considered it important to look at Hungary's import/export values at hourly resolution. For this purpose, we used the heatmap plot to display the median value of Hungary's import/export position (top row of Fig. 4), the probability that Hungary is in an import (middle row of Fig. 4) or export position at a given hour (bottom row of Fig. 4) in the cases 1B, 2B and 3B. Based on 40 years' data, we have plotted the frequency of export and import positions on a relative scale, represented as probabilities. The probability that Hungary is in an import/export position at a given hour is obtained from the sensitivity analysis using 40-years' renewable energy capacity factors by simulating the possible electricity market of year 2030 assuming that the meteorology (thus the availability of weather dependent renewable energy sources) would develop during the year 2030 like in one of a given years from the last 40 years. According to this calculation, if Hungary was in an import position 40 times out of 40 years in a given hour, then the probability of importing in that given hour is 100 %, and if Hungary was in an import position 0 times out of 40 years in that given hour, then the probability of importing in that hour is 0 %. Intermediate values between 0 and 1 are represented by the relative value of the frequency.

The analysis shows that in Portfolio 1, Hungary's electricity system is mostly in an export position from February to November in the middle of the day (8 a.m.–2 p.m.) and in the early morning hours from August to November due to the baseload generation of nuclear capacity and the production of Hungarian solar capacity. It is important to note that, despite the high exports in this portfolio,

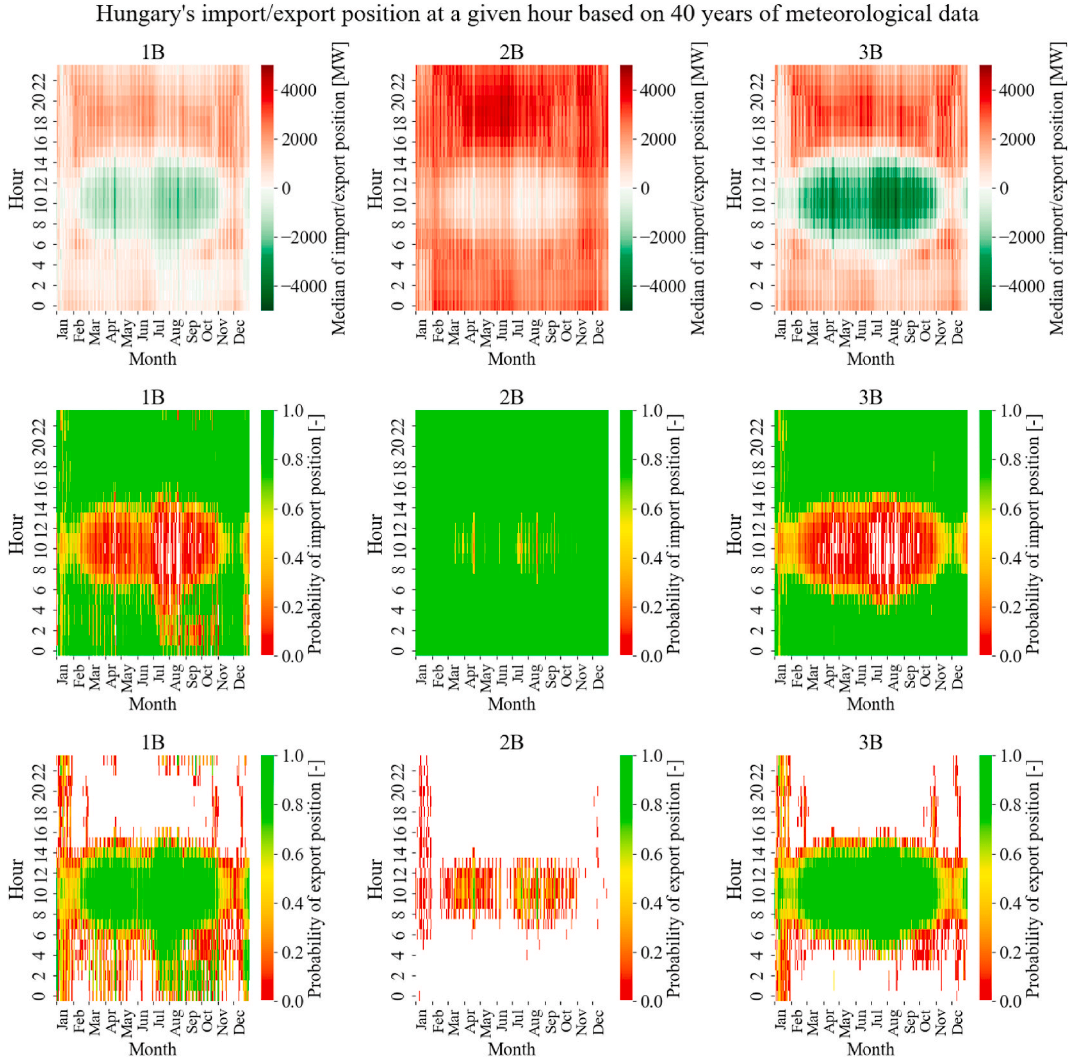

Fig. 4. Median values of Hungary's hourly import/export position in 2030 (top), probability of its import position (middle) and probability of its export position (bottom) based on 40 years of meteorological data.

the country can only meet its needs in the evening hours all year round and in the January–July and November–December periods at dawn only through electricity imports. In Portfolio 2, the situation is much more gloomy, as the country has to import much larger amounts of electricity and, except for a few hours during the day, the country also needs to import electricity on a continuous basis. In Portfolio 3, one can see that both the import size (due to increased consumption) and the export size (due to surplus solar capacity in the system) increases compared to Portfolio 1, and the dawn export positions disappear.

The analysis of weather-dependent renewables shows that the import/export positions occur mostly in the same period, but it is also important to note that the sensitivity analysis shows that Hungary may take an electricity exporting position in the market in the winter months in all three portfolios.

In the course of the studies, we also addressed the issue of unserved electricity in Hungary. The simulations show that in Portfolios 1 and 3, with an annual volume of 10–20 GWh and a maximum capacity of 3000 MW, and in Portfolio 2, with an annual volume of 20–140 GWh and a maximum capacity of up to 5000 MW, there is unserved demand in the Hungarian system. It is emphasized that this unserved electricity in Hungary is there despite the fact that the model also includes the power plants of the neighboring countries and that the Hungarian border capacities are available with the real values, so that the unserved electricity cannot be produced by the system of the 7 countries under study together. We have examined whether, in the hours when unserved electricity occurs in Hungary, there would be enough spare cross-border capacity to meet this shortfall from the systems of countries beyond our neighbors. This analysis showed that for each of these events there is sufficient spare cross-border capacity, so that this demand could in principle be imported from countries beyond our neighbors. These conditions could be further investigated by extending the modelled domain, since even though Hungary has free cross-border capacity at a given hour, there may still not be sufficient export capacity in the continental European system.

3.2. Production of electricity from different energy sources

In order to assess the carbon-neutral electricity generation targets, it is essential to look at the energy mix of electricity generation in Hungary. The country has committed to the European Union that 90 % of its electricity generation will come from carbon neutral sources and 21 % from renewable sources by 2030. Given the fact that Hungary has been relying on significant electricity imports for a long time, it is worth examining these shares not only for electricity production but also for electricity consumption in the country, considering all non-domestic sources as fossil sources, since Hungary currently imports mainly from countries where lignite-fired power plants are dominant (this assumption is also supported by Fig. 6). The results are presented in Fig. 5. The carbon neutral energy sources included nuclear, run-of-river hydro, reservoir hydro, pumped-storage hydro, wind, solar, geothermal, biomass, waste-fired, biogas-fired power plants and lithium-ion battery energy storage, while renewable energy sources include run-of-river hydro, reservoir hydro, pumped-storage hydro, wind, solar and geothermal.

In Portfolios 1 and 3, Hungary exceeds its commitments for the share of carbon neutral and renewable energy sources, if we define these shares for domestic production (Fig. 5, left column), however, for the shares defined for domestic consumption in Portfolio 3, the role of natural gas and imports in the electricity supply is already too high, so that even taking into account the fluctuations of renewables, the share of carbon neutral electricity does not reach 90 % (see top right graph in Fig. 5).

The situation is much less favorable in Portfolio 2: the median value of the simulation results for the share defined for domestic production is just below 90 %, and only in years with very favorable meteorology does the share of carbon neutral fuels reach 90 %. The effect of the variability of weather-dependent renewables is estimated to be between 3 and 4% for these shares. In the case of consumption, the share of carbon neutrality is less than 60 %. Fig. 5 shows very illustratively that, due to the high import share, the commitment to carbon neutral and renewable shares could be significantly evaded by carbon leakage [40], if we do not consider the sources from which the imported electricity actually comes. In our view, looking at the share of energy sources in consumption gives a more realistic picture.

The modelled cases provide an opportunity to examine the impact on the regional market of the two new VVER-1200 nuclear power units in the Paks 2 project, as the comparison of Portfolios 1 and 2 shows how the production of energy sources in the region changes, thus which energy sources would replace the production of the new Paks units if they were not built for some reason.

The results are presented in Fig. 6 and three main conclusions can be drawn:

- The 20.9 TWh of nuclear-based electricity generated by Paks 2 in Portfolio 1 will be replaced in Portfolio 2 by 70 % natural gas-fired power plants and to a lesser extent by biomass and lignite-fired power plants, thus significantly increasing the region's carbon emissions.
- The Paks 2 project has no detectable impact on renewable energy production, no market loss from new Hungarian nuclear units for the renewable energy sources and this is true for all 40 years of the sensitivity analysis.
- The big losers in the non-nuclear portfolio are the region's pumped-storage hydro power plants and Hungarian batteries, since with the loss of Paks 2 there is less low variable cost electricity on the market to fill the storages economically, so their utilization is significantly reduced between the two portfolios.

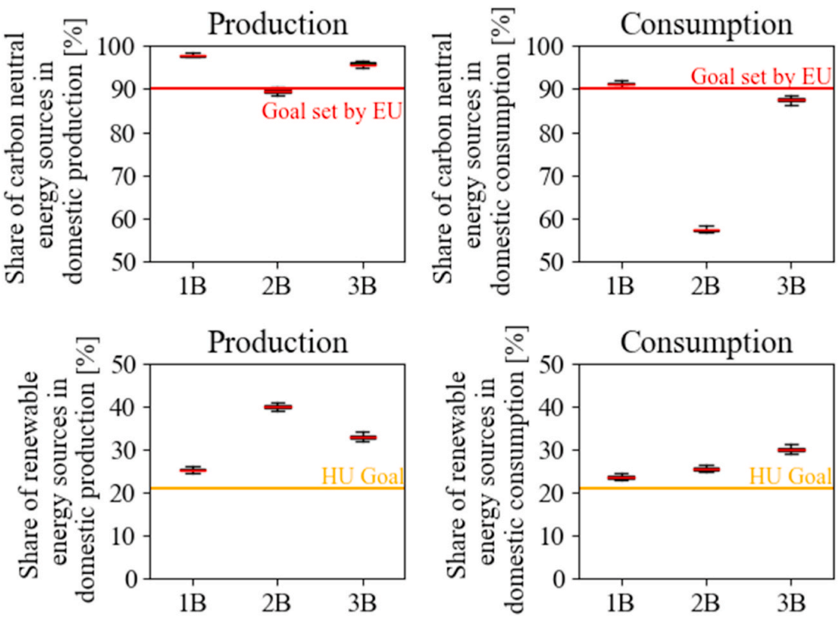

Fig. 5. Carbon-neutral (top) and renewable (bottom) shares of Hungary's electricity production (left-hand column of the graph) and electricity consumption (right-hand column of the graph).

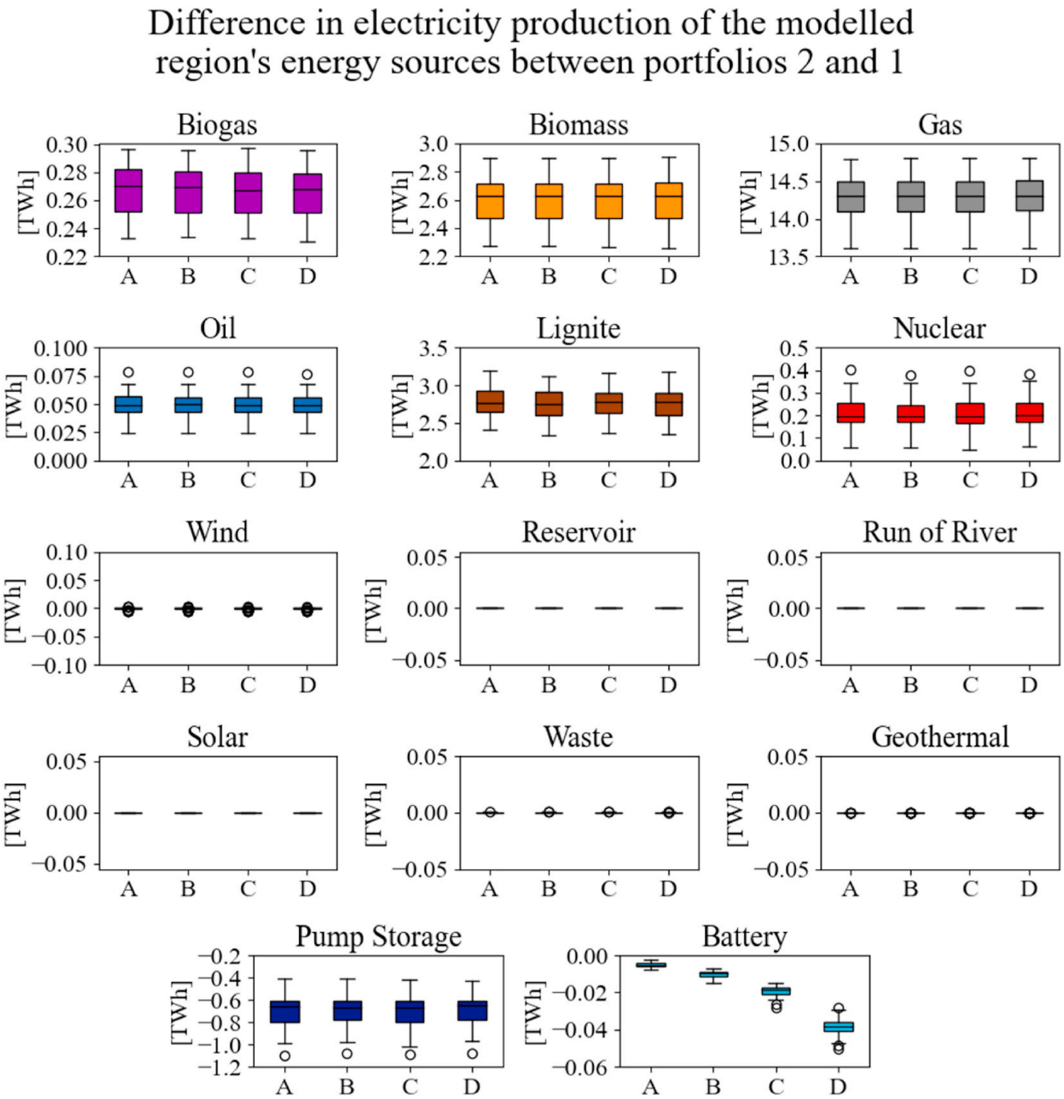

Fig. 6. Difference in energy production in the region between Portfolio 2 and Portfolio 1.

3.3. Lithium-ion batteries

The results for battery performance are summarized based on the results of Portfolio 1, with little difference in battery performance between Portfolios 2 and 3. In PLEXOS, battery operation is optimized for the difference between the electricity price used for charging and the electricity price received by selling the electricity during discharge, considering the variable battery operation and maintenance costs given in Fig. 17 in Appendix B. The optimization of the batteries is solved by the PLEXOS model in 1-day steps as described in Section 2.1.

A more accurate model of battery operation in 2030 could be obtained if their utilization is not only optimized for price arbitrage, but also if they participate in reserve markets [41] and if the availability fee is included in battery revenues. However, the creation of a model that includes the aforementioned market products was not the subject of this research, but we plan to address this in the future.

First of all, for the batteries, the amount of electricity (TWh) they charge and discharge and the capacity factor defined for the batteries in Section 2.3 were examined and are shown in Fig. 7. The analysis of Fig. 7 shows that as the capacity of batteries increases, the amount of electricity for charging and discharging increases at a greater than linear rate, as well as the battery capacity factor. It is also important to note from the data in Fig. 7 that even for 8 h of storage capacity (Scenario D), the battery's total annual capacity factor is less than 50 %.

We also looked at the length and number of these events, in addition to the amount of charges and discharges. In Fig. 8, the left column shows the data for discharge and the right column shows the data for charge. The average number of events per year is also shown in the upper right corner of the graphs.

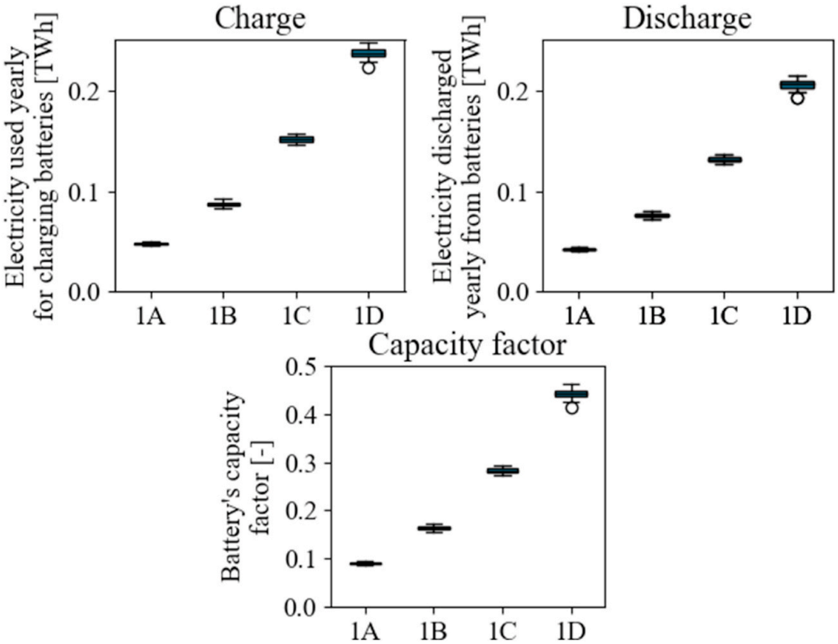

Fig. 7. Charge and discharge volumes (top graphs) and total capacity factor (bottom graph) of the Hungarian battery park in different battery scenarios for Portfolio 1.

The analysis shows that in all scenarios, the number of 1-h events is the highest for both discharge and charge, but the proportion of short events becomes smaller as the battery capacity increases. In Fig. 8, it is important to note that there are several events in the plots that are longer than the battery storage capacity in hours, suggesting that the battery power capacity is not being used to its full potential in all hours. Fig. 8 shows that the duration of battery usage is 1100 h in Scenario A and 1400–1500 h in the higher capacity scenarios, resulting in an average of 1.5 or 2 charge-discharge cycles per day for the battery park. The distribution of charge-discharge cycles per day and per year is shown in Fig. 18 in Appendix C for Portfolio 1. It can be clearly seen that the batteries are discharged regularly during the evening peak demand period.

In Fig. 9, we have displayed in the matrix format we have used several times before (e.g. in Refs. [17,37,42]), whether the Hungarian battery park is empty (white), charging (red), discharging (blue) or storing energy (grey) at a given hour, based on the hourly resolution input data for 2019. (This figure does not show the effect of the fluctuations of renewable energy sources, for this purpose see Fig. 10). It is important to note in Fig. 9 that on average there are not one but two charge-store-discharge cycles per day. The first cycle is in the early hours of the morning, while the second cycle is mostly around 12 noon for charging and between 18 and 20 h for discharging. The results in Fig. 9 also demonstrate that as the storage capacity increases, the storage role of batteries decreases and charging and discharging start to dominate. This is also in line with the total annual number of charging cycles shown in Fig. 8. In order to get a better overview of the usage of the battery during the day and the change of usage between months, in Appendix C the monthly average hourly state of charge (Fig. 19.), charging (Fig. 20.) and discharging (Fig. 21.) power values of the battery are plotted during the day in scenario 1B, in the case of input data from 2019. These figures also support the statements of this paragraph about the usage of the battery during the day.

The impact of renewable energy fluctuations on batteries is shown in Fig. 10, where the annual share of different battery statuses is plotted as a function of scenarios. The analysis of Fig. 10 confirms that increasing battery capacity increases the share of charges and discharges, while decreasing the number and share of states when the battery is empty. The proportion of storage states does not change between Scenarios A and B, but the aforementioned decrease is already visible in Scenarios C and D. Renewable energy sources have a significant impact on the batteries due to their fluctuating production, with up to 7 % difference in the share of a given battery state between years, depending on the weather.

To investigate the return on investment in battery storage, the specific profit of batteries was determined using Eq. (1). To calculate the return on investment, we used the specific investment costs described in Ref. [43] published in June 2021, which gave a specific investment cost of $800/kW for 2-h battery storages. Since no data was provided for 1-h storage, we assigned this value to 1-h storage. For the 4-h storage $1400/kW and for the 8-h storage $1900/kW was used (which was given for the 6-h storage in the literature cited).

The analysis in Fig. 11 confirms that the specific profit between 1 and 2 h of storage does not decrease significantly, but does decrease for 4 and 8 h of storage, as in these scenarios the storage cannot benefit from such a large price difference. Moreover, the payback shown on the right side of Fig. 11 shows that the 2-h batteries are the most suitable for batteries that generate revenue purely from the price of electricity purchased and sold, as they have the lowest payback time in this scenario, but it should also be noted that the maximum 20-year lifetime, indicated by the red line on the righthand side of Fig. 11, as reported in the papers [44–50] cited also in Ref. [43], is exceeded in all scenarios. This suggests that for battery energy storage investments to be profitable at such investment

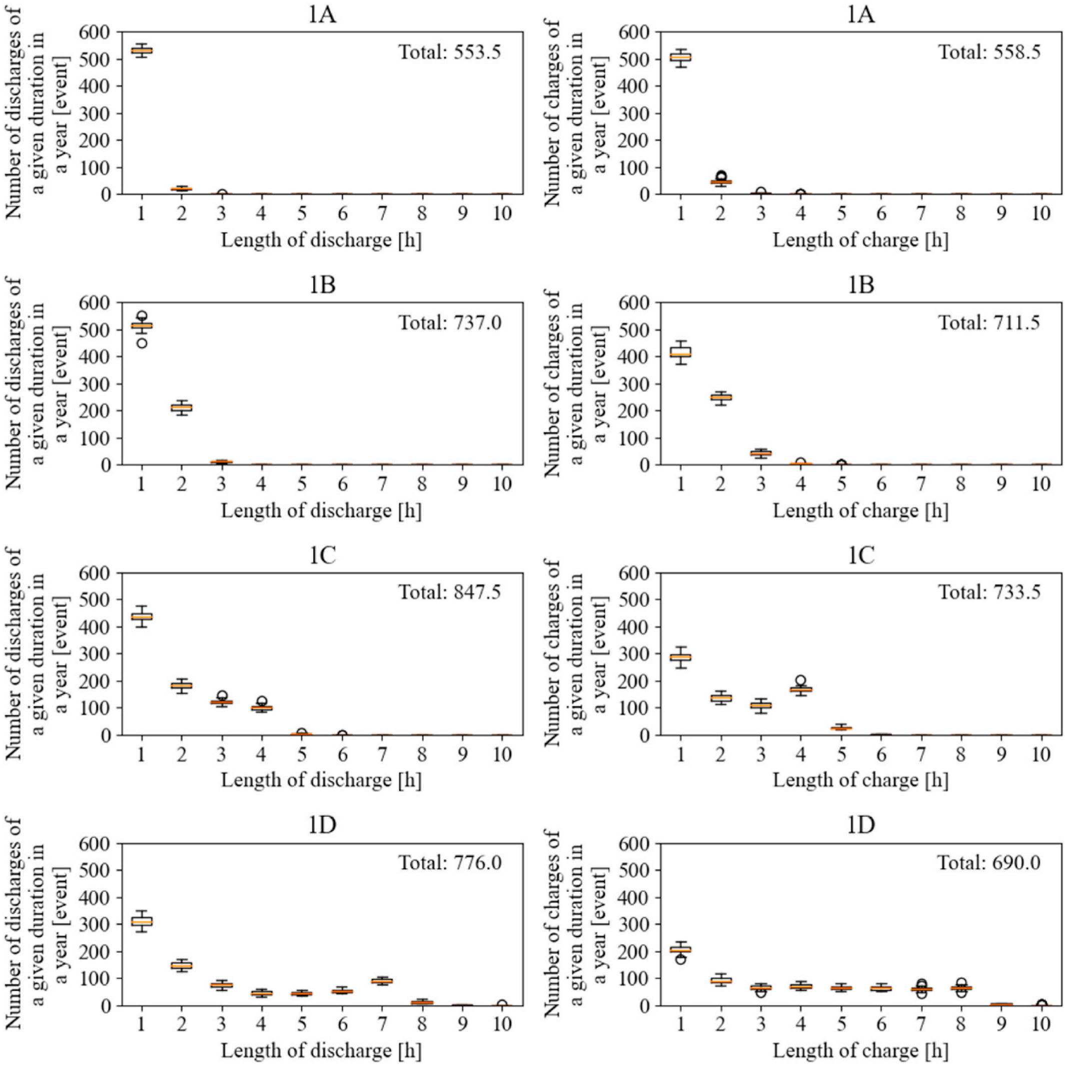

Fig. 8. Frequency of charging/discharging events of the Hungarian battery fleet as a function of event length in different scenarios for Portfolio 1.

costs, they need to participate also in balancing markets and generate revenue through up- and down balancing products, in addition to price arbitrage. The numerical results presented here are consistent with the findings in the literature [51–53].

3.4. Emissions of carbon-dioxide

Despite the large installed weather-dependent renewable energy generation capacity, there may be many system conditions where these sources cannot operate close to their nominal capacity, and fossil sources must be called upon instead. This results in carbon dioxide emissions, for which specific annual values are shown in Fig. 12. The specific carbon dioxide emissions of fossil-fired power plants are equal to the value defined in Ref. [42]. In all three portfolios Hungary has favorable data in this respect, as even in the worst Portfolio 2 the specific CO2 emissions of the country's electricity system do not exceed the EU average projected for 2030, which is expected to be around 100 gCO2/kWh according to Ref. [54]. These favorable values are also due to the fact that in 2030, according to the Hungarian NECP [28], there will be no coal-fired power plant in the system, while case 2B has almost three times higher specific emissions than 3B and almost five times the emissions of case 1B.

It is also important to add that the values in Portfolio 2 would be much higher if the carbon dioxide needed to generate imported electricity and burned abroad were added to the Hungarian values, since, as shown in Fig. 6., more than 80 % of the Paks 2 nuclear power plant's generation is replaced by fossil-based electricity.

These hourly resolution specific carbon-dioxide emission data can be very useful input data for a life cycle analysis (LCA) [55,56] that takes into account in which country a product is produced and during which periods it buys electricity from the system, so we make these data sets available as supplementary material in.csv format. Please see details at the end of the paper.

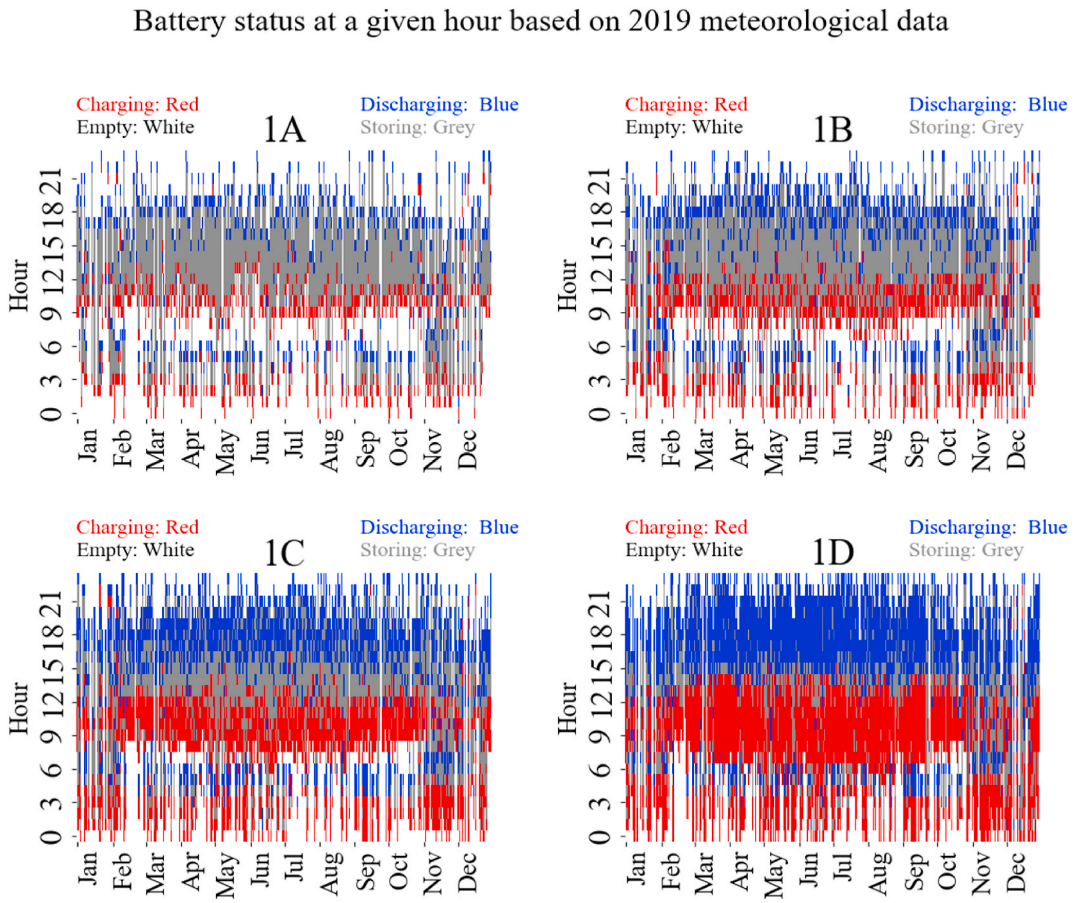

Fig. 9. Hourly evolution of battery status based on 2019 meteorological data in different scenarios for Portfolio 1 in year 2030.

3.5. Price of electricity

At the beginning of this work, both Europe and Hungary were in the grip of an energy crisis [57], triggered by the sharp rise in the price of natural gas due to the Russian-Ukrainian war and the rise in the price of electricity, which closely follows the price of this energy source due to the market mechanism. In this context, we considered it of utmost importance to analyze the price developments on the Hungarian electricity market in 2030.

The PLEXOS model's price duration diagram for the Hungarian electricity market is shown in Fig. 13. In the analysis, we have also considered the influence of the fluctuations in the availability of weather-dependent energy sources on the prices in the Hungarian electricity market. The uncertainty values resulting from the simulations using 40 years of meteorological data are shown in Fig. 13 with the pale-colored bands.

The analysis of the portfolio values shows that in Portfolio 2, the price of electricity in the Hungarian system is \$1000/MWh in 2030 for 300 h due to the energy not supplied. This value is the price set in the model for unsupplied energy, as described in Appendix B, Section B5. A further lesson from the figure is that in Portfolio 2, in the absence of Paks 2, the market price will be higher for more than half of the year due to the loss of the low-priced electricity generated by Paks 2 in the other two portfolios. There is no significant difference between Portfolio 1 and Portfolio 3, but clearly higher values will be seen in Portfolio 3 at certain times of the year.

A sensitivity analysis of the impact of renewables shows that the price on the Hungarian market is volatile in the 1000 h associated with the highest value, and in the hours when a more expensive producer is entering the market in the merit order model.

In addition to the data from the duration diagram, it is also important to analyze the hourly distribution of electricity prices using the familiar matrix plot. Due to the small difference between Portfolios 1 and 3, only data from Portfolios 1 and 2 are presented in Fig. 14, in which we have displayed the minimum (top), average (middle) and maximum (bottom) prices on the Hungarian market at a given hour based on 40 years of renewable generation.

The figure shows that while the vast majority of the hours in Portfolio 1 between April and August fall into the yellow and green (1-\$200/MWh) price range, this is more the case for the May–June period in Portfolio 2. It is also important to recognize the periods of highest prices, which typically fall in the months of November–February, when high load conditions typically occur in the Hungarian system.

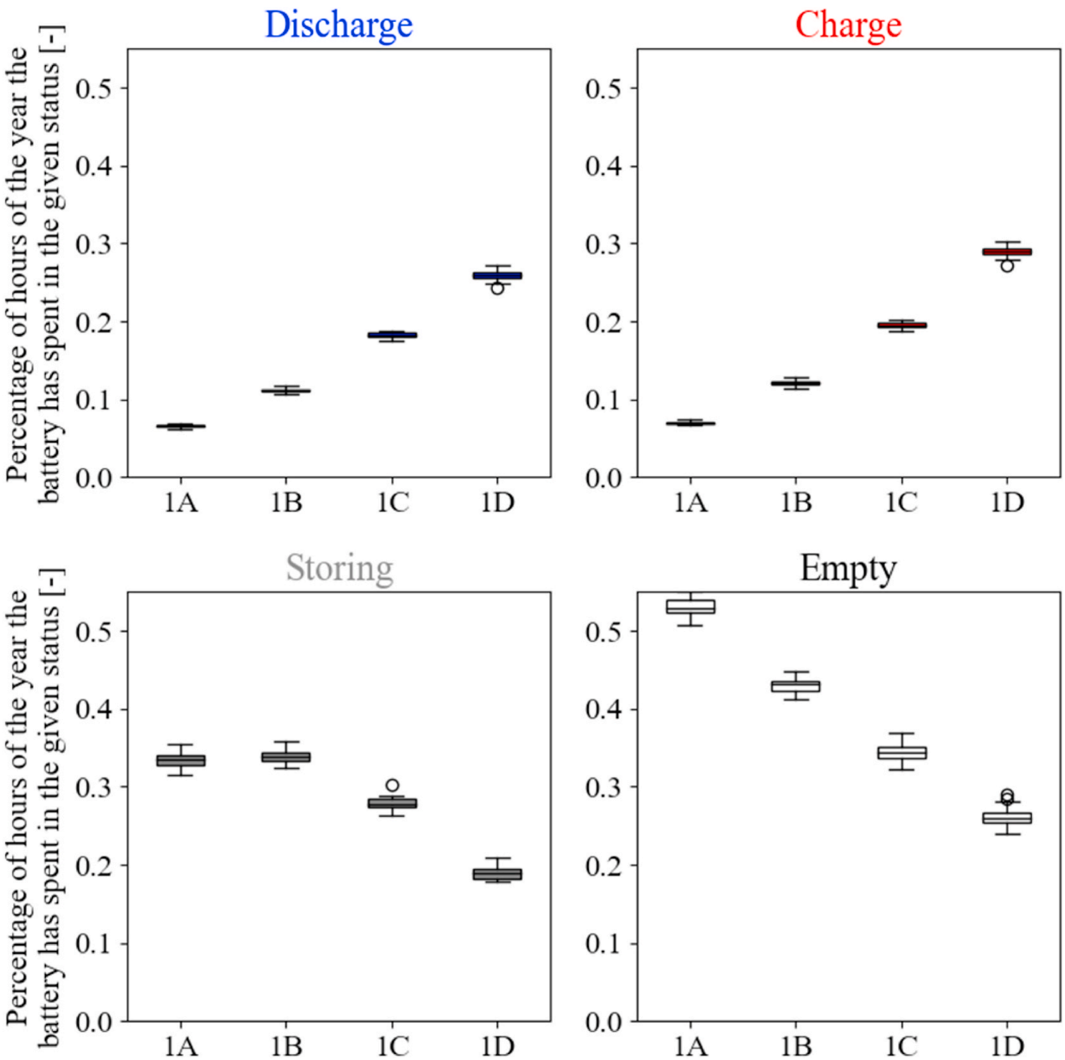

Fig. 10. Proportion of different battery statuses as a function of scenarios for Portfolio 1.

These electricity price data with hourly resolution can be important for economic calculations of energy investments (energy storage [58] or electrolysis [59] installations) that are subject to large price fluctuations over time and are therefore made available as supplementary material in.csv format, allowing the data to be used as input in other calculations.

3.6. Nuclear power plant capacity factor

Finally, we also examined the operating characteristics of the Hungarian nuclear power plant capacities. Evidently, an increase in the capacity of weather-dependent renewable energy sources may have an impact on the operation of nuclear units and will require more flexibility in the system to maintain a balance between generation and consumption. For this purpose, the frequency of different capacity factors of Hungarian nuclear capacities was investigated using simulation results.

Fig. 15 is special in two respects. On one hand, the capacity factor of nuclear power plants has been categorized with 5 % incremental steps so that the upper value of the category no longer appears in the category, and cases where the nuclear power plant is operating at full capacity, i.e. 100 % of the hourly capacity factor, have been examined separately. The other peculiarity of Fig. 15 is that the y-axis is cut into two separate parts, missing the part between 140 and 8450 h, so that both the low and high values can be seen clearly on the graph.

The calculational results show that in 2030 the nuclear power plants will continue to operate as baseload generators for 97 % of the year, i.e. their capacity factor will be 100 %, but they will have to operate in a dispatchable mode for 3 % of the year to compensate for the fluctuations of renewables in the Hungarian electricity system. (This is of course only true if the current merit order model remains in place in the electricity market.)

From the results in Fig. 15, it is also important to highlight that in each portfolio there are occasions (12 in Portfolio 1, 2 in Portfolio

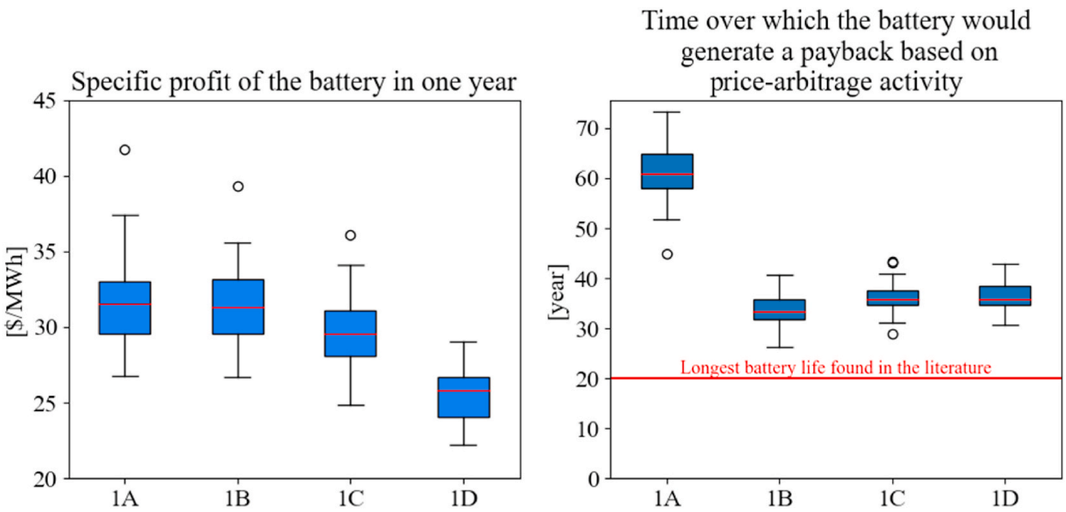

Fig. 11. Specific profit (left) and return (right) of the Hungarian battery fleet in different scenarios for Portfolio 1.

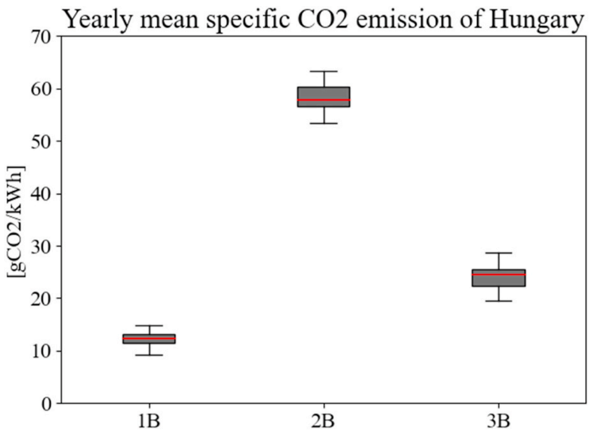

Fig. 12. Carbon intensity of electricity generation in Hungary for different portfolios.

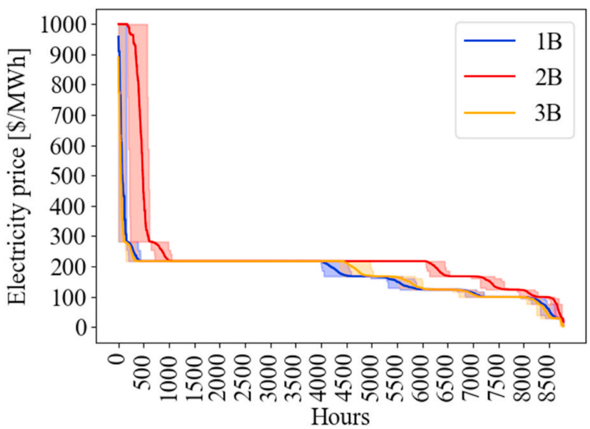

Fig. 13. Duration diagram of prices in the Hungarian electricity system for different portfolios.

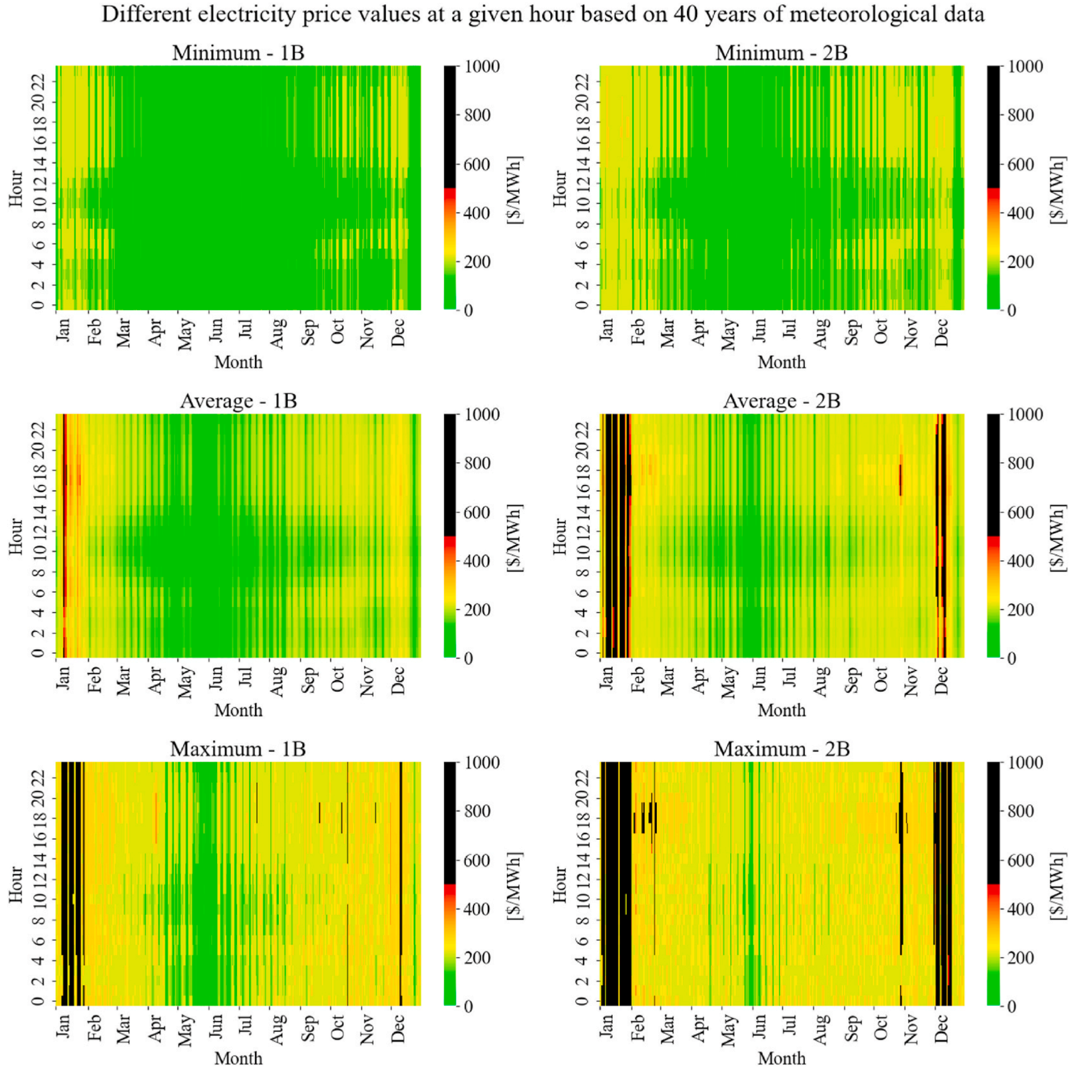

Fig. 14. The minimum (top), average (middle) and maximum (bottom) hourly electricity prices in the Hungarian electricity system in Portfolios 1 and 2, using 40 years of meteorological data.

2 and 13 in Portfolio 3) when the software decides to shut down the Hungarian nuclear power plants completely due to high renewable energy supply. From a technical and operational point of view, this situation is strange, as the minimum down time of 18 h is given as input data for the nuclear units (see Appendix B, Section B1, Fig. 16), so if a nuclear unit is shut down, it should also remain at 0 power for at least 18 h. It is easy to see that these conditions should be avoided. During the hours when renewable penetration is high (typically around noon), it may seem rational to shut down a nuclear plant. But after a few hours, when solar generation is decreasing and other capacity is needed, the long minimum down time will prevent nuclear plants from coming back online, forcing fossil fuel plants to increase production. So, the CO2 emissions and the electricity price in the system for those 18 h – when the nuclear plants are shut down – will be much higher than if some of the renewables would have been disconnected from the grid in those few hours. These simulation results will also depend heavily on the CO2 quota and the price of natural gas, which will determine the variable cost of fossil inputs during the lifetime of the nuclear power plant.

It is also worth mentioning the difference between the results of Portfolios 1 and 3 in Fig. 15, which shows that the increase in solar capacity from 6400 MW (Portfolio 1) to 12 000 MW (Portfolio 3) has a significant negative impact on Hungarian nuclear units, even though the country's consumption also increases significantly between the two portfolios (from 57.6 TWh to 68 TWh). For the

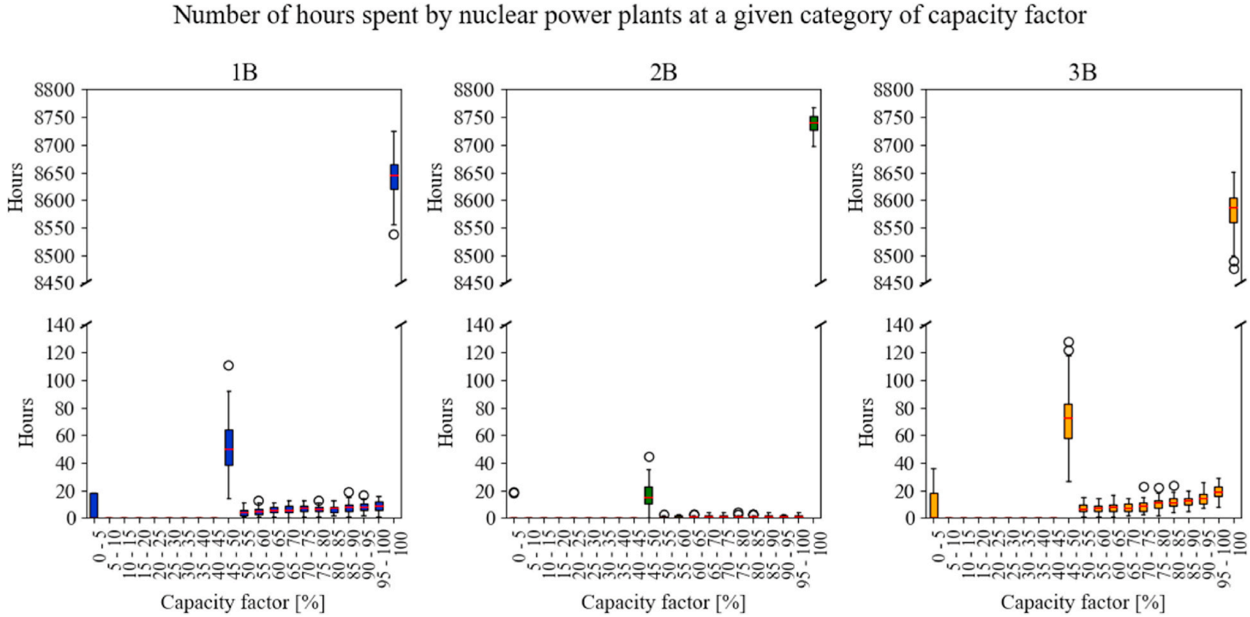

Fig. 15. Distribution of the capacity factor of Hungarian nuclear power plants in different portfolios.

operators of nuclear power plants and the TSO responsible for the stable operation of the system, this statement carries an important message, as they have to take into account that a situation may arise in the electricity market of the region under study where Hungarian nuclear units may have to be shut down for longer periods, given the high renewable penetration. This problem raises the question of whether the Hungarian electricity system can cope with such a large amount of solar PV capacity and foreshadows a line of research that tries to remedy the difficulties of these system states by various energy storage, hydrogen production capacities and solar PV inverter interventions. As mentioned above, these problematic system states are not frequent, but are complicated both from an engineering and an economic point of view, and thus deserve further investigation in the future.

4. Conclusions

Electricity supply in Europe, especially in Central Europe, faces a number of challenges. In the short term, it has to cope with increased prices due to the consequences of the Russian-Ukrainian war, and in the long term, it has to play a significant role in decarbonizing the economy while meeting security of supply targets and remaining affordable. The energy sector will undergo significant changes to meet these challenges, and this is particularly true for the electricity system. The power industry faces three major challenges in the near future: replacing fossil fuels, reducing Russian fossil fuel imports and keeping prices affordable. We do not yet have a clear, sustainable solution to these problems, which is why high-resolution simulation and analysis of these systems is crucial.

In this paper, we have analyzed the National Energy and Climate Plans of Hungary and its neighboring countries in order to quantify their plans for annual electricity consumption, installed capacity and cross-border capacity in 2030 and to take them into account in the simulations. To build as accurate as possible models of the countries' electricity systems in 2030 in PLEXOS software environment, a detailed literature study was conducted on the technical and economic parameters of conventional power plants, renewable power plants, pumped-storage hydro plants and battery electricity storage.

After processing the data, we built a model of the electricity system in Hungary and neighboring countries (Slovakia, Romania, Serbia, Croatia, Slovenia and Austria) for the year 2030 in the electricity system modelling software PLEXOS. Three power plant portfolios were analyzed as a function of Hungarian electricity consumption and power plant capacity, and four different scenarios were analyzed to investigate the impact of the potential capacity of the Hungarian battery park on system. A sensitivity analysis was carried out to quantify the uncertainty of weather-dependent power generation, based on the hourly resolution capacity factors of solar and wind power plants, taking into account data for the last 40 years.

Based on the calculation results, it is clear that if the NECP targets are met, Hungary will still be in a net electricity import position in 2030, but the level of imports will vary significantly depending on whether or not the Paks 2 nuclear power plant will be available at the time. Our analysis suggests that Hungary's electricity system will be in an export position for most of the year in Portfolios 1 and 3 where new nuclear units are in the Hungarian system, while in Portfolio 2 it will remain a net importer of electricity.

The results suggest that Hungary can only meet the 90 % carbon neutrality electricity production target with the commissioning of Paks 2, while if we define the carbon neutrality target for electricity consumption, only Portfolio 1 will reach the desired value. Our analysis also shows that in Portfolio 2 without Paks 2, almost 90 % of the lost nuclear-based generation is replaced by fossil fuels, thus significantly undermining the achievement of the CO2 emission targets.

The studies also provide a wealth of important insights into the possible operation of lithium-ion batteries in 2030. The values for batteries show that they have in average daily 1.5–2 charge-storage-discharge cycles, and even for batteries with 8-h capacity (Scenario D) they are actually used in less than 50 % of the year. The hourly pattern of the battery data shows that a charge-storage-discharge cycle occurs in the early morning hours as well as during the day, and that increasing capacity is associated with a decrease in storage time.

Based on the economic data of the storage facilities, it can be stated that the 1-h (Scenario A) and 2-h (Scenario B) storage facilities have the highest profit per unit of electricity discharged, while the lowest is clearly in Scenario D. Our analysis confirms that currently the most cost-effective option is to install 2-h battery storages. However, it is also important to note in relation to batteries that, at the assumed investment costs found in the literature, battery investments will not be profitable through pure price arbitrage activities and will need to participate in balancing markets and generate additional revenue through up- and down balancing products to be profitable investments.

The results on carbon-dioxide emissions and electricity prices show that the two new 1200 MW nuclear units will have a clear positive impact on Hungary's electricity supply.

The paper also presents important results on the utilization of nuclear units in Hungary. The calculation results for the nuclear power plants show that they will continue to operate as baseload generators for more than 97 % of the year, but will also have to contribute to the balancing of the system as dispatchable plants. To achieve this flexibility, the development of flexible operation of nuclear power plants and the related research and development are essential. The calculation results indicate that only a very small number of hours in the month of June (maximum 0.4 % of the hours studied) should be expected to lead to a situation in the system where nuclear plants would have to be shut down due to excessive renewable penetration. Specific analysis of these system states is proposed.

The electricity system in Hungary and the neighboring countries will undergo a major transformation by 2030, with more weather-dependent and less conventional capacity in the region, reducing system flexibility. The results presented show that the Paks 2 investment is essential to maintain a high level of security of supply in the Hungarian electricity system and to meet the country's CO2 emission targets in 2030.

As previously demonstrated [17], it is not sufficient to model the future state of the electricity system on the basis of annual energy balances or reference period calculations, but simulations of electricity supply at hourly resolution are necessary for high weather-dependent penetration. Sensitivity analysis carried out to investigate the effects of fluctuations in renewable energy sources show that the variable production of weather-dependent energy sources (solar and wind) and their variability between years make it worthwhile to perform simulations based on as many years as possible available. Simulations using many years of data significantly increase the reliability of results by quantifying uncertainties.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Bence Biró: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Attila Aszódi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Data for the countries modelled

The aggregated data of the 2030 annual consumption and installed capacities used as inputs in the model are presented in Table 2, with a special focus on the values of the 3 defined Hungarian scenarios. Table 3 shows the cross border capacities between countries in 2020 and 2030.

Table 2
Annual 2030 consumption [TWh] and installed capacity [MW] as input in the PLEXOS model

Country	HU			AT	HR	RO	RS	SI	SK
Scenario	1.	2.	3.						
Demand [TWh]	57.6	57.6	68	85	20	65.9	41.5	15	39.5
Nuclear	4 400	2 000	4 400	0	348	1 975	0	348	2 880
Solar	6 400	6 400	12 000	7 044	768	5 054	1 540	1 650	1 200
Wind	329	329	329	7 211	1 364	5 255	3 510	150	500
Run-of-river hydro	58	58	58	5 543	549	3 440	2 729	1 199	1 304
Reservoir hydro	0	0	0	2 965	1 856	4 153	629	0	451
Pumped-hydro storage	0	0	0	2 971	281	746	642	180	916
Biomass	796	796	796	696	148	137	0	90	200
Waste	100	100	100	103	0	0	0	0	0
Biogas	0	0	0	0	0	0	0	34	200
Geothermal	3	3	3	0	17	0	0	0	4
Battery	100	100	100	0	0	0	0	0	0
Natural gas	2 400	2 400	4 000	3 301	1 048	2 958	0	1 555	1 153
Lignite	0	0	0	0	192	1 980	4 000	689	0
Oil	0	0	0	164	0	100	0	0	0

Table 3
Import/export capacity of modelled cross border capacities in 2020 and 2030 (data source [60])

From	To	2020 capacities [MW]		2030 capacities [MW]	
		Export	Import	Export	Import
AT	**HU**	800	800	1 200	800
AT	**SI**	950	950	1 200	1 200
HR	**HU**	2 000	2 000	2 000	2 000
HR	**RS**	600	600	600	600
HR	**SI**	1 500	1 500	2 000	2 000
RO	**HU**	1 100	1 000	1 400	1 300
RS	**HU**	600	600	600	600
SI	**HU**	1 200	1 200	1 200	1 200
SK	**HU**	2 000	2 000	2 000	2 000
RO	**RS**	1 000	800	1 300	1 300

As part of the sensitivity analysis, we had to modify the consumption series to include leap years. Our approach to treat leap years by providing hourly consumption data for the day 29 February was as follows.

First, we looked at the day on which February 29 fell in the period 1980–2019, and categorized the day as a weekday, Saturday or Sunday depending on this. In the next step, we defined a day in 2019 for each category to replace the missing 24-h consumption value for leap years. For leap days of the 40 years under question falling on the weekdays we substituted February 28, 2019, for Saturdays we substituted March 2, 2019, and for Sundays we substituted March 3, 2019 consumption data.

Appendix B. Description of technical and economic parameters of power plants

An extensive literature study was carried out on the technical and economic parameters essential for the PLEXOS simulations. In each case, the energy sources found in the literature were classified into the 14 categories of energy sources studied, and all values for cost data were converted to 2022 US dollars. Where the literature defined minimum, average or median and maximum values for a given parameter, we used the average or median value in all cases. The values obtained were averaged out and this value was given as input data. We deviated from this logic only for the fuel cost of natural gas, because during the period when the simulations were performed (end of 2022 - beginning of 2023) the price of natural gas was well above 100 USD/MWh at the Dutch TTF market [59]. Accordingly, the natural gas price in the calculations was 110 USD/MWh.

However in the period of finalizing this paper (March 2024), the international natural gas prices went down remarkably, inducing much lower price forecast for 2030, therefore it was also considered important to examine a case with lower natural gas prices. During this test, a natural gas price of USD 50/MWh was set in the model, which is based on our literature study. The main change as a result of this was that natural gas fired power plants had a lower marginal cost of production (reduced from 218 USD/MWh to 118 USD/MWh) than biomass fired plants, i.e. the natural gas fired power plants were placed ahead in the merit order. Figures for these cases can be found in the Supplementary material.

A comparison of Fig S2 and Fig. 3 shows that Hungary's annual import position increased by 2 TWh in each Portfolio due to the change in the price of natural gas from 110 USD/MWh to 50 USD/MWh), which is due to the exchange of positions of the natural gas and biomass in the merit order (see Fig S1 and Fig. 2), as it was more economical to operate foreign natural gas power plants instead of Hungarian biomass power plants. The increase in this position can also be seen between Fig S3 and Fig. 4, and it can be observed that the 50 USD/MWh natural gas price has increased the probability of import and decreased the probability of export positions of Hungary.

The reduction in natural gas prices also had a negative impact on the share of carbon neutral and renewable energy sources in the Hungarian electricity system. As can be seen in Fig S4 and Fig. 5, the share of carbon neutral generation and consumption has decreased by 5–10 %, while the share of renewables in generation and consumption has decreased by 8–13 % due to the loss of the market for biomass. Fig S5 and Fig. 6, which show the difference between the first and second Portfolios, also show the reversal of the roles of natural gas and biomass due to the lower natural gas price, as while the production of natural gas between Portfolios increased by 1 TWh, the electricity production based on biomass between Portfolios decreased by more than 1.5 TWh.

The 60 USD/MWh reduction (from 110 to 50 USD/MWh) in natural gas prices has had a significant negative impact on battery utilization (see differences between Fig S6 and Fig. 7), the annual number of charge and discharge events (comparison between Fig S7 and Fig. 8), and the battery states when the battery is not empty (differences between Fig S8 and Fig. 9, and also between Figs. S9 and 10). This negative effect is due to the fact that the fall in the price of natural gas reduces the intraday price differential on which the battery relies for to make profit with its operation. Consequently, it is easy to see that battery returns also deteriorate significantly, as shown by the significantly different results in Fig S10 and Fig. 11.

As mentioned above, the decrease in the price of natural gas has increased the role of natural gas in the market, which clearly implies that the specific carbon dioxide emissions of Hungary's electricity system will increase significantly in case of lower natural gas prices (see Fig S11 and Fig. 12). The only positive contribution of the decrease in natural gas prices is the decrease in the price of electricity in the Hungarian system, as can be seen from the difference between Figs. S12 and S13, and also between Figs. 13 and 14. The only thing, that was not affected by the decrease in natural gas prices was the capacity factor of the Hungarian nuclear power plants, as can be seen from the comparison between Fig S14 and Fig. 15.

In Fig. 16, the parameters that can be found in the literature are plotted, and as supplementary material, the average of the parameters found in the literature is given in csv format, which also serves as input for the models built in this research. In Fig. 16, for waste and biogas energy sources, some values are not shown in the figures. This is because no values were found for the parameters given in the literature for these energy sources. In all cases, these missing values have been replaced by the value of the biomass energy source.

B1. Conventional power plants

Conventional power plants include all power plants that produce some form of thermal energy and then convert it into electricity. On this basis, the following power plants are included in this group: nuclear power plant, coal-fired power plant, natural gas-fired power plant, oil-fired power plant, geothermal power plant, biomass-fired power plant, waste-fired power plant, biogas-fired power plant. The technical and economic parameters that influence the electricity production of the power plants in the model are as follows:

- Maximum capacity [MW]: defines the nominal net capacity of the generating units in megawatts.
- Minimum stable level [MW]/factor [%]: minimum stable production level of each generating unit. This is the fraction of power at which the unit can still operate, but below this level the generating unit cannot operate and must be shut down. The factor is the minimum stable production level defined as a percentage of maximum capacity.
- Heat rate [GJ/MWh]: Proportional to the reciprocal of the efficiency of the plant, considering the conversion between units (ratio of heat consumed to electricity produced).
- Up/down ramp speed [MW/min]: defines the speed at which the plant is ramped up from zero to minimum stable level and ramped down from minimum stable level to zero.
- Minimum up/down time [hours]: the minimum number of hours during which the unit must be in the 'on' or 'off' state in any commitment cycle.
- Variable O&M cost [$/MWh]: a component of the incremental cost of generation; used to recover O&M costs incurred as a direct function of generation.
- Fuel cost [$/GJ]: the cost per unit of fuel used by a power plant.
- Carbon dioxide production [kg/GJ]: determines the CO2 emission rate as a function of fuel consumption. Based on [61], this value is set to 103 kg/GJ for natural gas, 197 kg/GJ for oil and 211 kg/GJ for coal.
- Carbon dioxide quota [$/kg]: represents the incremental cost of CO2 emissions. This value was taken from the exchange price of the carbon-dioxide quota on January 01, 2021 based on [62], which corresponded to $0.03/kg.

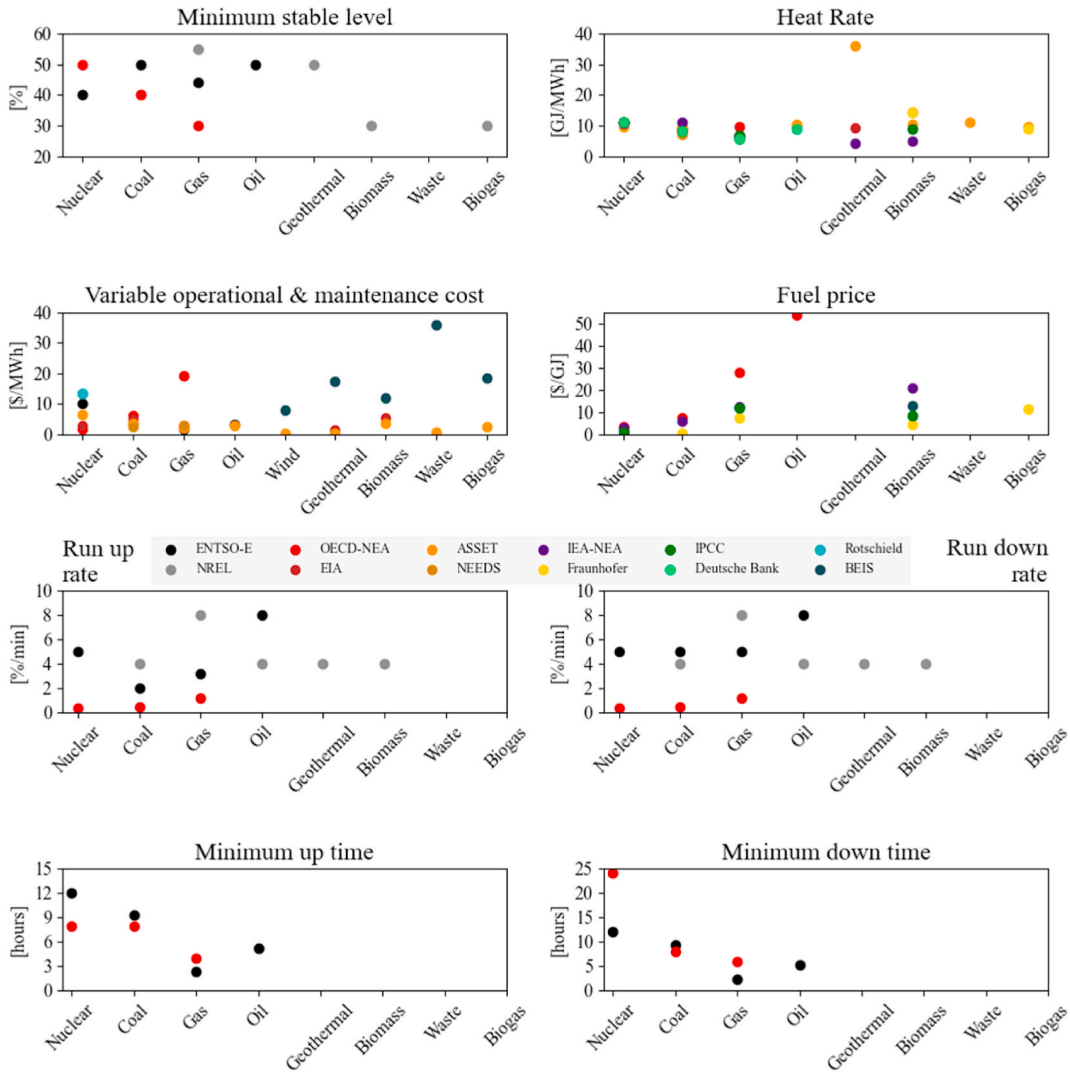

Fig. 16. Results of the literature study on the technical and economic parameters of conventional power plants (data source [61,63–74], own representation).

B2. Power plants based on renewable energy sources

In this category, we included solar, wind, run-of-river and reservoir hydro, as the hourly production of these plants is highly dependent on weather conditions, which we wanted to reproduce in the model. For these power plants (as for conventional power plants), we defined maximum capacity and variable O&M cost characteristics, and for each plant we defined an hourly resolution capacity factor (which is the percentage of installed capacity that the plant can produce in each hour) according to the weather conditions in the country in 2019. For solar and wind, these capacity factors were retrieved from the Renewables.ninjas database (the data from which are described in Refs. [75,76]) due to the shortcomings of the ENTSO-E database presented in Ref. [17]. For run-of-river and reservoir hydro, as no other data were available, we used the 2019 hourly resolution of generation and 2019 installed capacity to generate the required hourly values of the capacity factors, which were downloaded from the ENTSO-E and MAVIR databases, as for the consumption datasets, qualitatively evaluated and corrected for erroneous hourly values. For these data series, there have been situations where several consecutive hours have been missing. In this case, the erroneous values were replaced by interpolation between the two closest exact values (29 in Slovenia and 1 in Romania and Slovakia).

A detailed sensitivity analysis was carried out to quantify the variability of weather-dependent energy production. Within this framework, the capacity factor of solar and wind power plants was defined in the model not only based on 1 year (2019), but also on the basis of 40 years of data (1980–2019). As with the 2019 data, this data was downloaded from the Renewables.ninjas [75,76] database.

For the hourly capacity factor for run-of-river and reservoir hydro, we followed a similar approach as for the consumption data regarding leap years, i.e. we used February 28, 2019 data for weekdays, replaced Saturday data with March 02, 2019 and Sunday data with March 03, 2019 (the method used for the consumption data is described in Appendix A).

An important feature of reservoir hydro power plants is their ability to store energy through their water reservoirs. However, this feature can only be modelled adequately if we know the size of the reservoirs of the reservoir hydro power plants in the modelled countries and the amount of water flowing into the reservoirs per hour. Since such detailed data are not available at the time of this research, we assume that the behavior of the reservoir hydro power plants in 2030 will be similar to their market behavior in 2019 and their production is based on the capacity factor of their reservoir hydro power plants in the given country during 2019.

For hydropower modelling in general, it would be possible to model these energy sources more accurately if we knew the hourly resolution relationship between the capacity factor of all run-of-river power plants and the flow of the river on which they are located (so that sensitivity analysis can be made on these plants based on decades of flow data), as well as the size of the water reservoirs of the reservoir hydro power plants, the amount of water entering the reservoirs at hourly resolution, the power output of these power plants, the evaporation losses from the reservoirs, and the maintenance and outage statistics of the hydroelectric power plants. The collection of these data, and thus more accurate modelling of the various hydropower plants, is outside the scope of this research, but could be the subject of a separate study in the future.

B3. Pumped-storage hydro power plants

Pumped-storage power plants are one of the most important balancing elements in today's electricity systems. In PLEXOS, pumped-storage hydro power plant is optimized similarly to battery operation, so the software optimizes the difference between the price of the electricity used for pumping and the price of the electricity generated by letting the water through the turbine., considering the battery operation and maintenance costs given in Fig. 17. As with batteries, the market behavior of pumped-storage plants could be modelled even more accurately if the reserve market were modelled, but this was still not the focus of this research. This type of power plant is described in PLEXOS by the following characteristics:

- Maximum capacity [MW]: defines the capacity of the plant in turbine mode.
- Pump capacity [MW]: defines the maximum load that can be accommodated in pump mode.
- Total cycle efficiency [%]: describes the combined efficiency of pump and turbine.
- Reservoir size and initial value [GWh]: The maximum amount of water that can be stored in the reservoir and the amount of water in storage at the initial time. These values shall be given separately for the upper and lower reservoirs. The same data are given for both reservoirs.
- Variable O&M cost [$/MWh]: a component of the incremental cost of production and used to recover O&M costs incurred as a direct function of production.

The turbine and pump capacities and the size of the reservoirs of the pumped-storage plants defined in the model are summarized in Table 4. The results of the literature study on the parameters of a pumped-storage power plant are presented in Fig. 17. In the simulations, the average of the data shown in Fig. 17 was used as input data.

Table 4
Turbine, pump and reservoir capacity of pumped-storage power plants (data source [77])

	Austria	Croatia	Romania	Slovenia	Slovakia	Serbia
Turbine capacity [MW]	3 459	300	746	185	926	614
Pumping capacity [MW]	2 560	200	1 033	180	828	560
Storage capacity [GWh]	1 722	18.3	92	2.6	49.7	194

B4. Battery electricity storage

In the future, battery energy storage could play a major role in the storage of electricity during the day. Lithium-ion battery electricity storage is currently the most common. Such storage is defined only for the Hungarian system because, as described in Section 2.3, only the Hungarian NECP provides specific data for such storage. In PLEXOS they are described as follows:

- Capacity [MWh]: specifies the maximum amount of energy that can be stored in the battery storage. This value was not defined in the Hungarian NECP, so it was assumed arbitrarily as 100, 200, 400 and 800 MWh in Scenarios A, B, C, D.
- Maximum power [MW]: defines the total discharge power. This was taken as 100 MW. (This was the only data given in the Hungarian NECP.)
- Maximum/minimum state of charge [%]: defines the maximum and minimum level of charge allowed to be reached by the storage tank.
- Charge/Discharge Efficiency [%]: describes the efficiency of charging and discharging the storage.
- Variable O&M cost [$/MWh]: a component of the incremental cost of production and used to recover O&M costs incurred as a direct function of production.

The results of the literature study on the parameters of a lithium-ion battery electricity storage are presented in Fig. 17. In the simulations, the average of the data shown in Fig. 17 was used as input data.

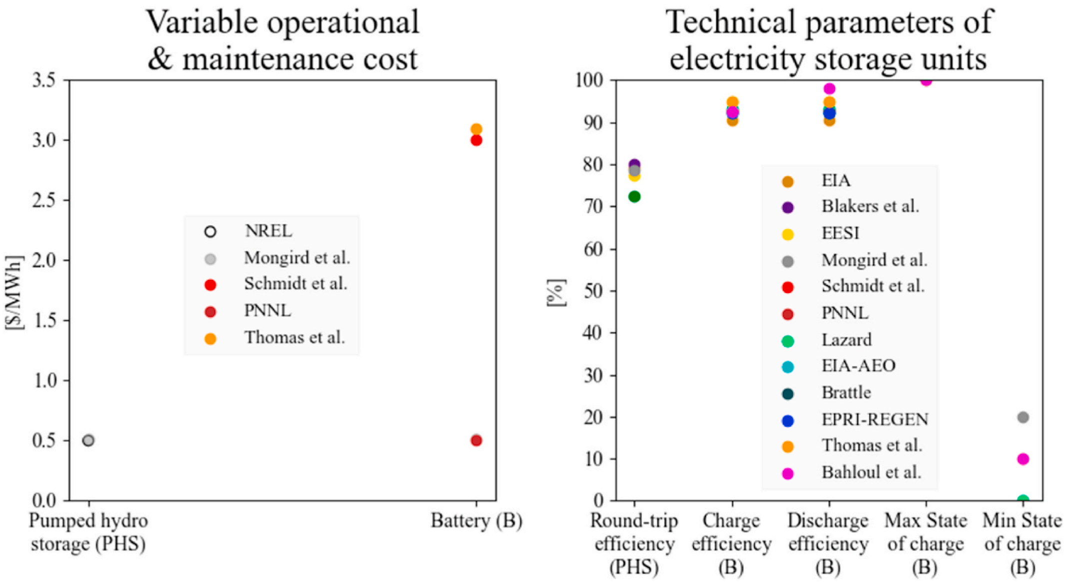

Fig. 17. Variable cost (left) and technical (right) data for pumped storage power plants and lithium-ion battery energy storage units in the literature (data source [44,47,49,50,78–87], own representation).

B5. Price of unserved energy

The PLEXOS model also requires the price of unserved electricity, which is related to the system state when there is not enough generation on the market to meet the demand of consumers at a given hour. When this system state occurs, this price will be set in the market. Its value is assumed to be 1000 $/MWh based on [88].

Appendix C. Additional battery figures

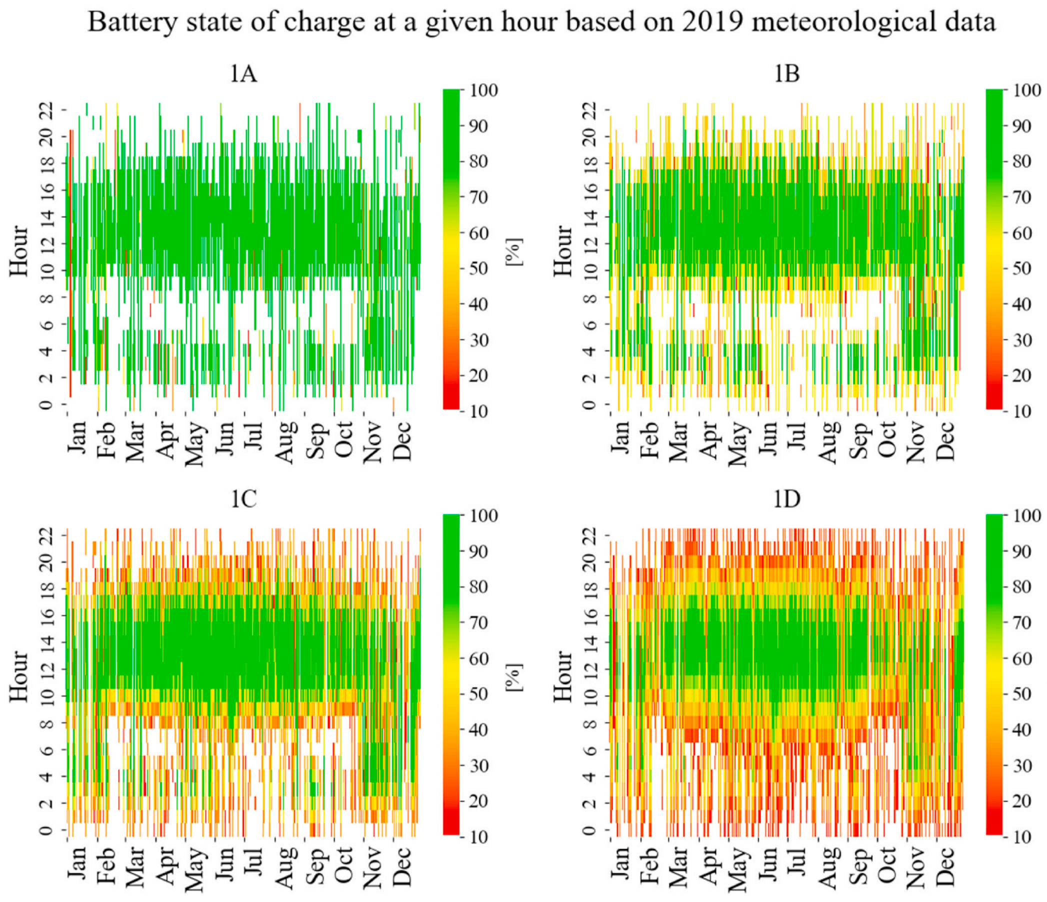

Fig. 18. Hourly resolution of the state of charge of the Hungarian battery fleet in different scenarios for Portfolio 1 in 2030 based on 2019 meteorological data.

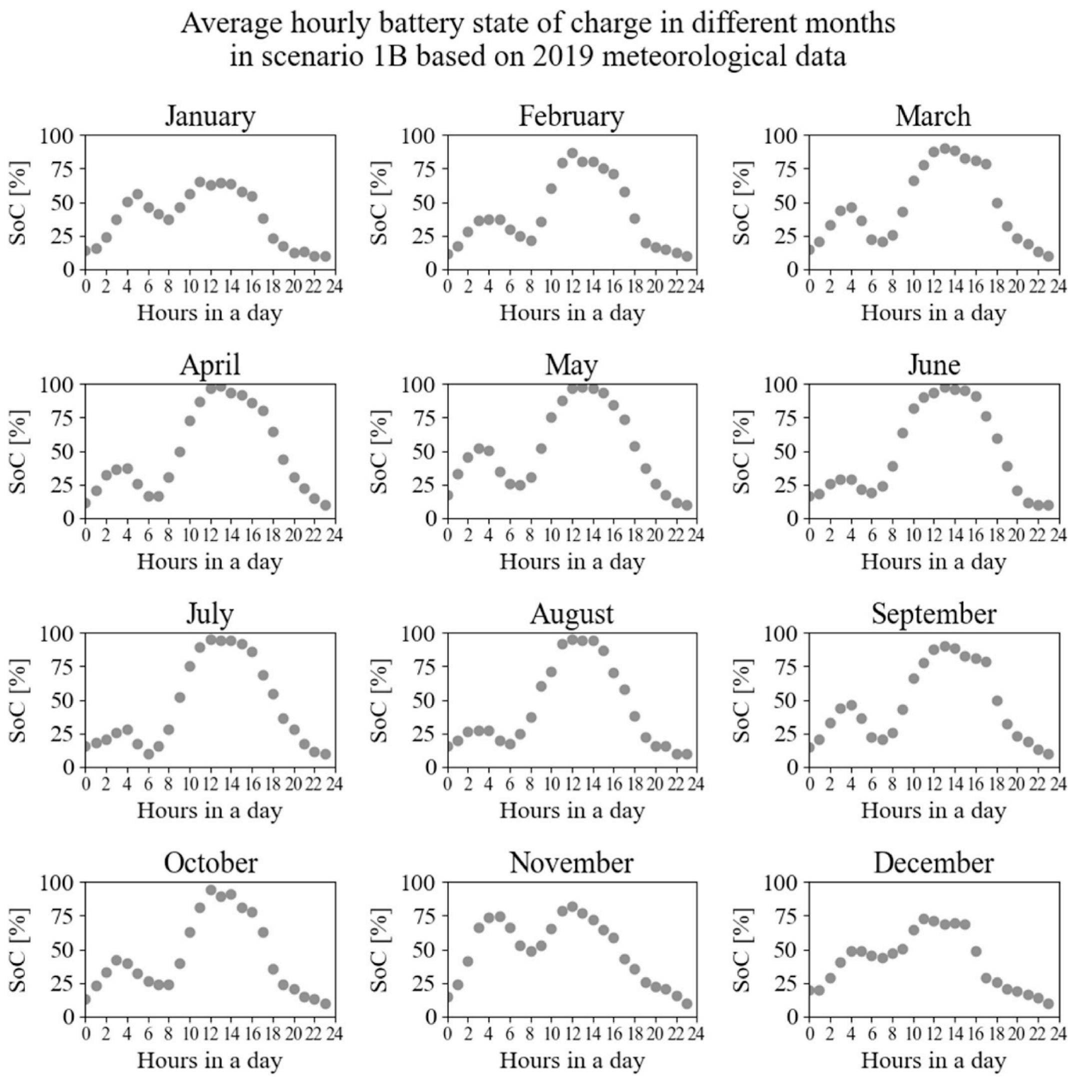

Fig. 19. Monthly average hourly state of charge (SoC) patterns of the battery during the day in different months in 2030 in the 1B scenario based on 2019 meteorological data.

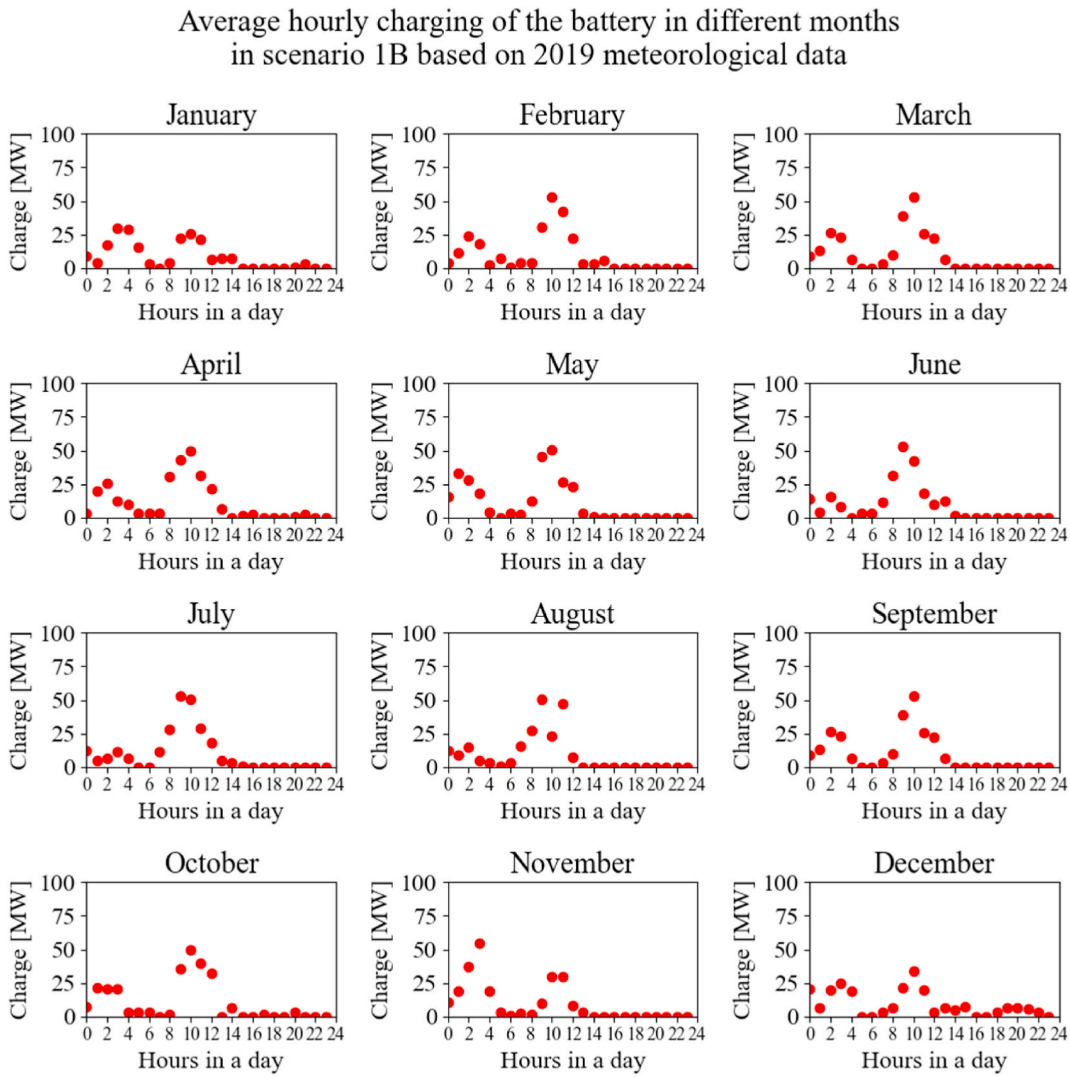

Fig. 20. Monthly average hourly charging power patterns of the battery during the day in different months in 2030 in the 1B scenario based on 2019 meteorological data.

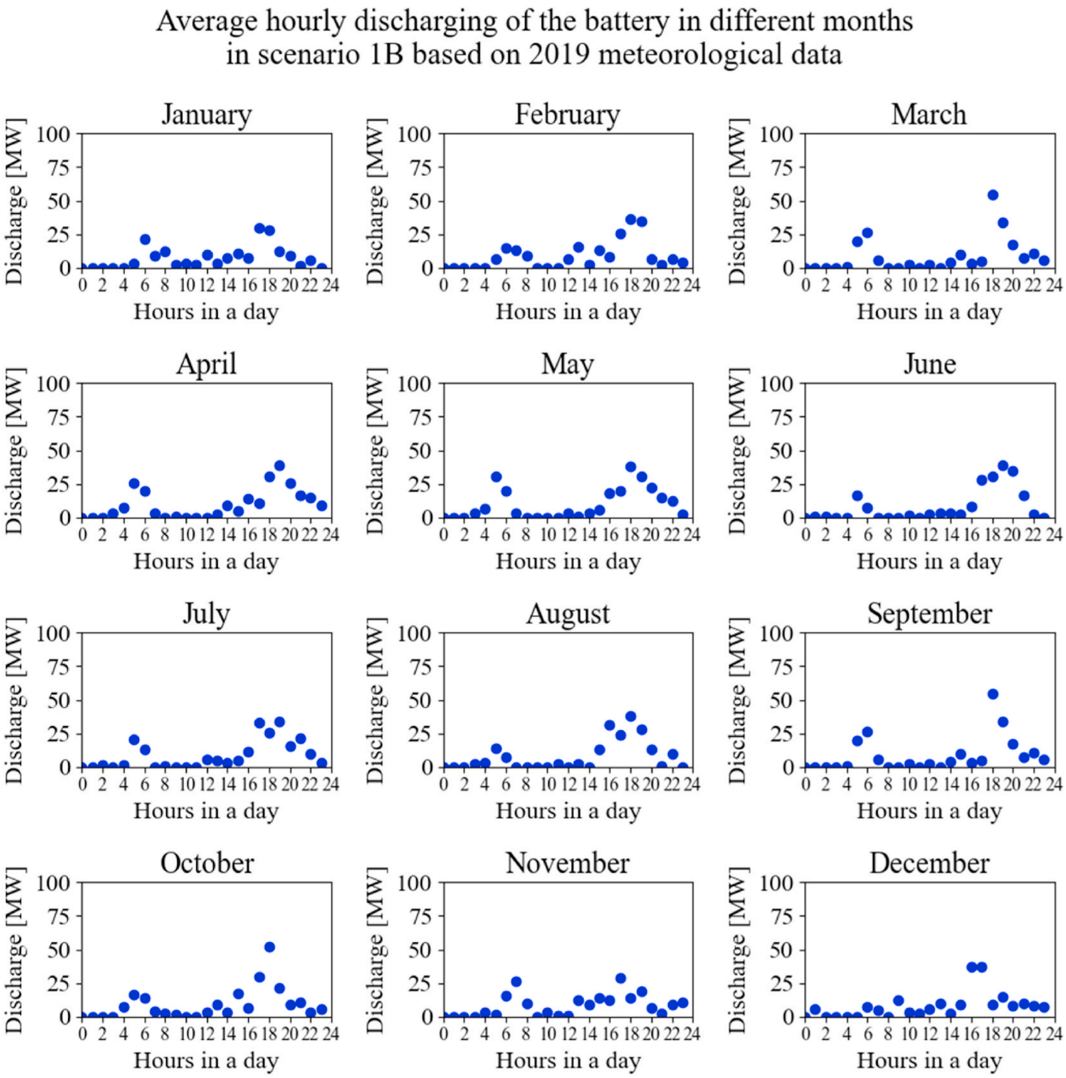

Fig. 21. Monthly average hourly discharging power patterns of the battery during the day in different months in 2030 in the 1B scenario based on 2019 meteorological data.

Appendix D. Supplementary data

As supplementary data, the technical and economic parameters of the power plants built into the PLEXOS model, and hourly data on the specific carbon-dioxide emissions of the Hungarian electricity system in 2030 and the system prices for all portfolios, all battery scenarios and all 40 years of the sensitivity analysis are available in csv format. Figures showing the results of the models for a natural gas price of USD 50/MWh are also available as supplementary material in a Word document. Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29841.

Abbreviations

AEO	Annual Energy Outlook
ASSET	Advanced System Studies for Energy Transition
BAU	business as usual
BEIS	Department for Business, Energy & Industrial Strategy
CCGT	combined cycle gas turbine
CO2	carbon-dioxide
EESI	Environmental and Energy Study Institute
EIA	Energy Information Administration
ENTSO-E	European Network of Transmission System Operators for Electricity

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ENTSOG	European Network of Transmission System Operators for Gas
EPRI	Electric Power Research Institute
ESST	Energy Scenarios Simulation Tool
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle analysis
LT	long term
MT	medium term
NEA	Nuclear Energy Agency
NECP	National Energy and Climate Plan
NEEDS	New Energy Externalities Developments for Sustainability
NPV	net present value
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OECD	Organization for Economic Co-operation and Development
PASA	Projected Assessment of System Adequacy
PNNL	Pacific Northwest National Laboratory
REGEN	Regional Economy, Greenhouse Gas, and Energy model
ST	short term
TSO	Transmission System Operator

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