Proceedings of the European Nuclear Young Generation Forum
ENYGF'23
May 8-12, 2023, Kraków, Poland

Investigating the cooperation between nuclear power plants and renewable energy sources in Central Europe using high-resolution simulations

Biró, Bence[1*] and Aszódi, Attila[1]

[1] Budapest University of Technology and Economics, Institute of Nuclear Techniques (BME, NTI), Hungary

*Corresponding author: *bencebiro@edu.bme.hu*

I. INTRODUCTION

The energy supply faces many challenges in the short and long term. The main elements of these challenges are tackling climate change and achieving sustainability, while also meeting security of supply objectives. To achieve the decarbonization goals, the electricity system in European countries will have to undergo significant changes, taking into account technical, environmental, economic and social aspects. The path towards achieving the targets will be further complicated by the ongoing Russian-Ukrainian war, which has led to a rise in energy prices and has resulted in European countries aiming to reduce their dependence on Russian fossil energy imports. Taking all these factors into account it can be concluded that the most important task for European countries are to replace fossil fuels, reduce Russian fossil energy imports and keep prices at affordable levels. Renewable energy sources and nuclear energy can play a major role in this task. However, there is still little data on how these technologies work together, so a detailed analysis of the cooperating electricity systems is essential.

In this paper, we perform a numerical analysis of electricity system in Hungary and neighboring countries. Our work includes mapping the countries' system-level electricity consumption in year 2030 and planned power plant portfolios and building hourly resolution simulations in Energy Exemplar's PLEXOS modelling environment. Our simulations show highly relevant results for the operation of nuclear power plants in a future electricity system (e.g. in the 2030s) with increasing share of weather dependent renewable energy sources.

II. Data and methods

In a previous paper [1], we have already shown that models based on reference hours modelling (e.g. TIMES), which are the basis for many National Energy and Climate Plans, are methodologically not appropriate in many cases. They may underestimate the importance of security of supply and do not accurately represent the timely distribution of weather-dependent energy sources' production. For the reasons described in [1], we use here hourly resolution models to model the electricity supply of countries in this paper to reproduce the variability of renewable energy sources with sufficient accuracy.

The main task in modelling the electricity markets at hourly resolution is to simulate which energy sources can supply the electricity to the market in order to cover the electricity needs, taken into consideration the timely changes in consumption, the differences in production costs, and the changing availability of weather dependent sources. This task has to be done while optimizing the total operating cost of the system and taking into account the operational constraints of the system components. To perform these tasks, we have chosen Energy Exemplar's electricity market software PLEXOS [2].

PLEXOS is a commercial power system modelling tool used for power market simulations. Within the framework of this research, a model was built in the PLEXOS environment in which the electricity system of the countries under study is represented by a single node (the transmission network of the countries was not modelled within the framework of this research) and the cross-border capacities between countries is represented by a pair of cross-border transmission lines per country. The model built has a time horizon of 1 year and a resolution of 1 hour. The software calculates the behavior of the electricity markets for one whole calendar year with hourly resolution in 1-day steps, so that the optimization takes into account the 24 hours before and after the day actually being calculated. In the model, power plants are considered at the level of energy sources, thus neglecting unit sizes, plant maintenance and unexpected outages.

A. Country data

The future of a country's electricity system is projected by its National Energy and Climate Plan, which has to be prepared by the national governments, so we have based our models on these official documents. We have analyzed Hungary and its immediate neighbors, except Ukraine. Ukraine was excluded from this study because the country's electricity system was connected to the European grid just recently and the transboundary capacity to be sold on the market is very small at this moment. On this basis, we have analyzed and modelled Austria (AT), Croatia (HR), Hungary (HU), Romania (RO), Serbia (RS), Slovenia (SI) and Slovakia (SK).

The countries' projected annual consumption and power plant portfolios at the source level for 2030 are defined in the model according to the countries' National Energy and Climate Plans. The consumption of countries in year 2019 and 2030 is shown in Figure 1, and the evolution of the installed capacity of energy sources is shown in Figure 2.

Figure 1 shows that all countries expect their electricity consumption to increase by 2030, driven by economic growth and the electrification of different sectors (industry, residential heating and cooling, transportation) according to their national strategies.

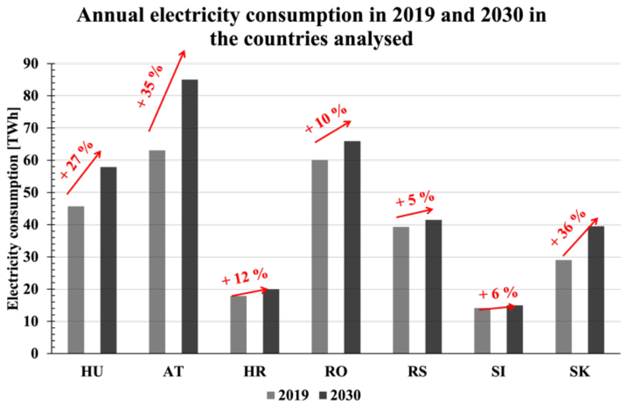

Figure 1. Annual electricity consumption in 2019 and 2030 in the countries studied (source of data for 2019 [3, 4] for 2030 [5–12], own representation)

The data presented in Figure 2 show that the installed capacity of electricity generators in the countries under study will increase significantly between 2019 and 2030. However, the energy source that the government of each country plans to use to cover this growth varies from country to country. Hungary and Slovakia plan to develop mainly nuclear and solar capacity, Romania plans to significantly increase its installed wind capacity, Croatia and Slovenia plan to invest in solar and natural gas, while in Austria and Serbia only solar and wind capacity is expected to increase in the coming years.

Cross-border interconnection capacity between the electricity systems of two countries provides a link between the two markets and creates the possibility for cross-border electricity trade. The interconnection capacities of the countries under study are defined according to [13].

To reproduce the effects of the pumped-storage power plants, it is not sufficient to define the installed capacity of these plants, but the turbine power, pumping power and reservoir capacity of the power plants must be given for each country concerned. Such precise data are not available in the National Energy and Climate Plan of the countries, therefore the above-mentioned parameters have been defined on the basis of the database referenced under [14].

Half of the electricity produced by the Krško nuclear power plant in Slovenia is used in Slovenia and the other half in Croatia (since Croatia owns 50% of the plant). By modeling this special circumstance in the Slovenian-Croatian interconnected grid a dedicated separate power line was assumed in the model between the two countries with a baseload operation exporting 348 MW (half of the installed capacity of the Krško NPP) from Slovenia to Croatia, and the Slovenian-Croatian cross-border capacity has been reduced by this 348 MW, to ensure a realistic utilization of the cross-border capacity.

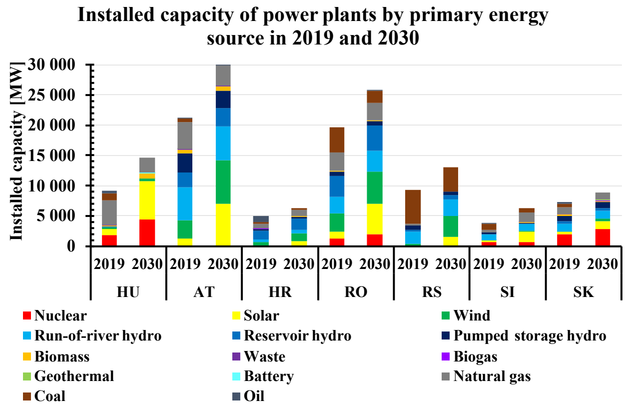

Figure 2. Distribution of installed capacity of power plants by energy source in 2019 and 2030 (source of data for 2019 [3,4] for 2030 [5–12], own representation)

B. Technical features of power plants

In order to describe the load variation limits of conventional power plants at the appropriate level, several technical parameters have been set for these capacities. The technical parameters are described as follows [15]:

- Minimum stable level [MW]/factor [%]: minimum stable production level for each production unit. Below this level, the production unit cannot operate and must be shut down. The factor is the minimum stable production level defined as a percentage of maximum capacity.
- Run-up / run-down rate [MW/min]: defines the rate at which the plant is ramped up from zero to the minimum stable level and ramped down from the minimum stable level to zero.
- Min up / down time [h]: The minimum number of hours in which the units must be in operation after being switched on / must not be in operation after being shut down.

For these parameters, the available literature was processed and the mean (column) and the minimum and maximum (error bars) of the values found in the literature were displayed in Figure 3. The mean values in Figure 3 were integrated into the model as input data. Since in this paper we model power plants only at the level of energy sources (not at the block level), the parameters presented in Figure 3 are also energy source specific.

C. Hourly data

We have also added hourly data to the model to simulate changes in electricity consumption and to reproduce fluctuations in weather dependent renewable energy production.

In order to determine the hourly consumption, the data for year 2019 were downloaded from the data publication website of the European Network of Transmission System Operators for Electricity (ENTSO-E) [3] for the neighboring countries and from the website of the Hungarian Electricity Transmission System Operator Zrt. (MAVIR Zrt.) [4] for Hungary. To determine the hourly electricity consumption distribution in year 2030 the 2019 hourly load data series was divided by the 2019 annual consumption and multiplied by the 2030 annual consumption, assuming that day-by-day and the intraday relative change of electricity consumption in year 2030 will match the 2019 hourly relative consumption changes. A more precise estimate could only be made if we had data on weather conditions in 2030 and the hourly impact of economic growth and electrification on consumption, but these data are not available right now.

For solar and wind power plants, the hourly resolution capacity factors were downloaded from the Renewables.ninjas [16] database (described in studies [17, 18]) due to the shortcomings of the ENTSO-E database presented in [1]. For run-of river and reservoir hydropower plants – as no other data were available – the required hourly capacity factor values were generated using the 2019 hourly resolution generation and 2019 installed capacity, which were downloaded from the ENTSO-E [3] and MAVIR [4] databases.

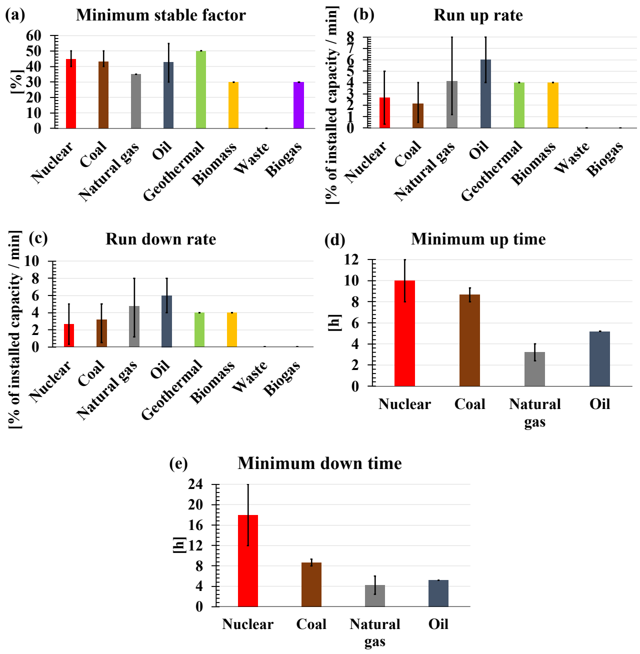

Figure 3. Minimum stable factor (a), run up rate (b), run down rate (c), minimum up time (d) and minimum down time (e) PLEXOS input for power plants (data source [19–22], own representation)

III. Results

We have already shown in previous studies [1, 23] that only countries that continue to rely on nuclear power will be able to meet the 90% carbon neutral electricity generation commitments set out in the European Green Deal [24]. These results therefore suggest that if countries really want to meet the commitments, they will need to apply nuclear power in addition to renewable power plants for their future electricity generation.

How renewable energy sources and nuclear power plants can co-exist will be crucial to the security of supply of future electricity systems, so in this article we have focused on the values associated with the operation of nuclear power plants in the results of our hourly resolution simulations. This study has resulted in very detailed data on the future capacity factor of nuclear power plants in the studied region.

First, we analyzed how the hourly capacity factor of nuclear power plants in concerned countries will evolve in 2030. The results of this analysis are summarized in Figure 4, where the specific frequency of utilization of nuclear units in four concerned countries is plotted. In Figure 4, we have treated separately the frequency associated with a hourly capacity factor of 0%, the other frequencies show values between 5 percentage points.

Our analysis in Figure 4 has the following main messages:

- Nuclear power plants in the region will continue to operate as baseload generators in 2030, as the capacity factor of each country's units will be 95% or higher for 99% of the hours of the year.
- Due to weather-dependent renewables and existing market mechanisms, nuclear plants will need to be dispatchable in 2030 to maintain system balance, so they will need to be ramped down to their minimum stable level for 40 to 45 hours of the year.
- As given in the results of the model calculations there are no system states in which the nuclear power plants are completely shut down. It means that – given the 18-hour minimum down time shown in Figure 3 – there is never a system state where the output of any country's nuclear units is not needed for more than 18 hours.

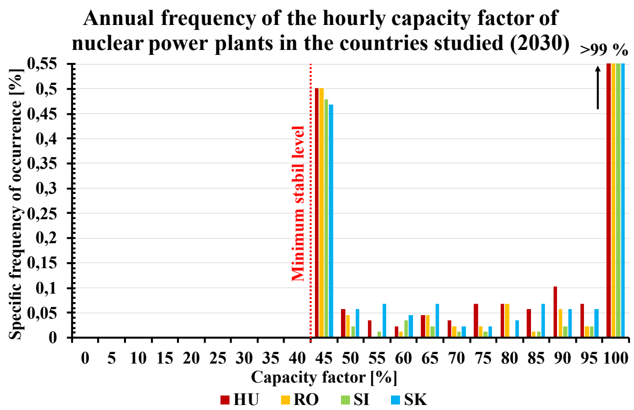

Figure 4. Annual frequency of the hourly capacity factor of the nuclear fleet of the countries under study in 2030

We also considered it important to analyze the hourly evolution of the capacity factor of nuclear power plants. For this purpose, the hourly capacity factor of nuclear power plants in 4 countries (HU, RO, SI, SK) for all 8760 hours of a calendar year is plotted in the form of a heat map in Figures 5 to 8. In Figures 5 - 8, the y-axis represents the hours of the day (1 - 24), while the x-axis the days of the calendar year (1 - 365), and the color of the given hour is defined by the color scale on the right y-axis. For the color scale, the values corresponding to a capacity factor of 45% are marked in white, and the values higher than 45% are plotted according to the color scale.

Our analysis presented in Figures 5 - 8 demonstrates that states where nuclear power plants are not operating at full capacity observed in Figure 4 can all be attributed to the May - July period within the year. The distribution of these system states within the day is more variable, but it is clear from our analysis that the vast majority of those system states occur between 8 and 14 hours. This is of course explained by the fact that the capacity factor of solar power plants is the highest during these periods [1]. The analysis of these system conditions is important because these system states can be reduced or even eliminated by new investments in system-level energy storage (e.g. batteries, pumped storage hydro, hydrogen production by electrolysers).

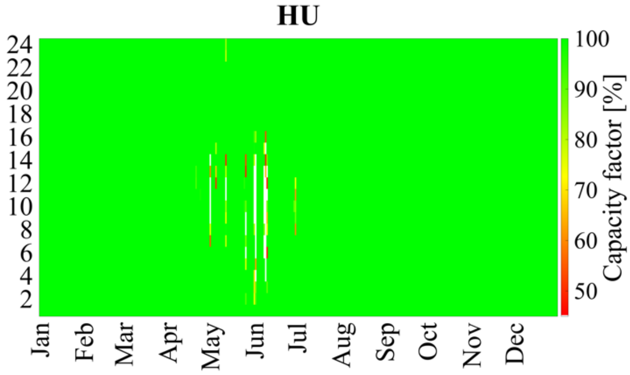

Figure 5. Hourly distribution of the capacity factor of the Hungarian nuclear fleet in 2030

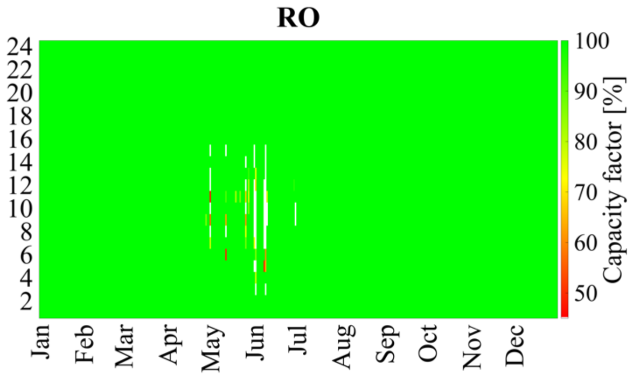

Figure 6. Hourly distribution of the capacity factor of the Romanian nuclear fleet in 2030

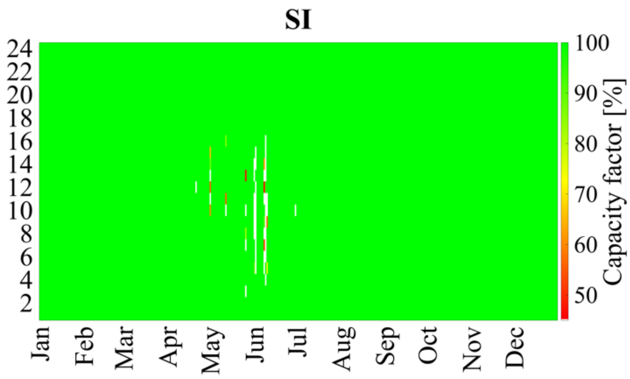

Figure 7. Hourly distribution of the capacity factor of the Slovenian nuclear fleet in 2030

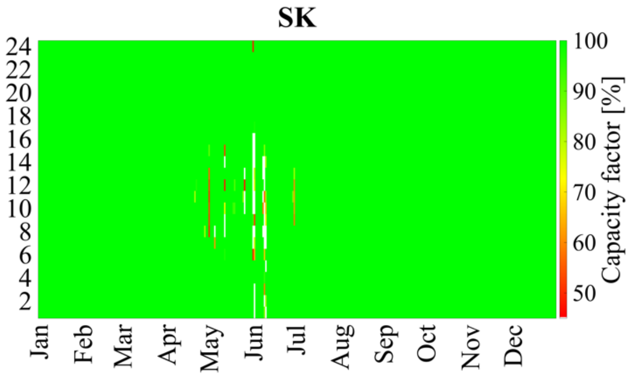

Figure 8. Hourly distribution of the capacity factor of the Slovak nuclear fleet in 2030

The Hungarian battery park with a capacity of 100 MWh and power output of 100 MW was also considered important to investigate. A one-hour storage was defined, as there is no corresponding data in the Hungarian NECP, and this research was not intended to investigate the capacity of storage under different scenarios, but it could be a promising topic for future research. To this end, we have plotted in Figure 9 whether the Hungarian battery park is empty (white), charging (red), discharging (blue) or storing energy (grey) at a given hour. The result in Figure 9 shows that on average there are about 500-550 charge-discharge cycles per year on a 100 MWh battery park, and from the analysis of the hourly data in Figure 9 it can be concluded that the Hungarian energy storage unit is charged at dawn and during the day and discharged during the morning and evening peak. The impact of the battery park on nuclear power plants could be determined by defining further scenarios, but these analyses were not in the scope of this research.

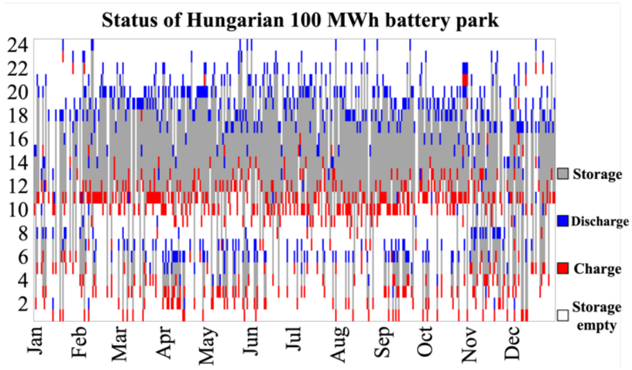

Figure 9. Hourly breakdown of Hungarian 100 MWh battery conditions in 2030

IV. Summary

In this paper, we have used very detailed, hourly-resolution simulations to investigate the future interaction of nuclear and renewable power plants in Central Europe. We have built a model to simulate the cooperating electricity markets of Hungary and its neighboring countries for year 2030 using the Energy Exemplar's PLEXOS modeling environment using data defined in the countries' National Energy and Climate Plans. The built model was also used to investigate the operation of a 100 MWh battery park in Hungary at high time resolution.

Our results clearly show that the nuclear power plants in the region will continue to play a baseload role for a significant part of the year in 2030, however these capacities need to be prepared also for flexible operation to compensate adequately the volatile renewable production.

In this article, we have used heat maps to illustrate the hourly load factor distribution of nuclear power plants over the year 2030 and highlight those periods of the year in which they will need to operate more flexibly. Our analysis suggests that the problematic time period in the 2030s will be May, June and July. The results presented in form of heat maps also point out that, in the future the challenging time periods – when nuclear power plants will have to take part in system level control due to high feed-in of weather-dependent generators – energy storage (e.g. batteries, pumped storage hydro, hydrogen production) could be a solution if these technologies would be present in the electricity system of studied region.

V. Acknowledgment

The research reported in this paper is part of project no. BME-NVA-02, implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021 funding scheme.

The research reported in this paper is also supported by the ÚNKP-22-2-I-BME-2 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

The research was also funded by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA).

VI. References

[1] A. Aszódi et al., "Comparative analysis of national energy strategies of 19 European countries in light of the green deal's objectives", Energy Conversion and Management: X, vol. 12, p. 100136, Dec. 2021, doi: 10.1016/J.ECMX.2021.100136.

[2] Energy Exemplar, "PLEXOS - The Unified Energy Market Simulation Platform", 2022, https://www.energyexemplar.com/plexos

[3] ENTSO-E, "Transparency Platform", https://transparency.entsoe.eu/

[4] MAVIR, "Website", https://www.mavir.hu/web/mavir/home

[5] Federal Ministry of Sustainability and Tourism, "Integrated National Energy and Climate Plan for Austria", 2019, https://energy.ec.europa.eu/system/files/2020-03/at_final_necp_main_en_0.pdf

[6] Ministry of Innovation and Technology, "National Energy and Climate Plan", 2020, https://energy.ec.europa.eu/system/files/2022-08/hu_final_necp_main_en.pdf

[7] Ministry of Economy, "Integrated National Energy and Climate Plan for 2021 to 2030", 2019, https://energy.ec.europa.eu/system/files/2020-03/sk_final_necp_main_en_0.pdf

[8] Ministry of Economy and Energy and Business Environment, "The 2021-2030 Integrated National Energy and Climate Plan", 2020, https://energy.ec.europa.eu/system/files/2020-06/ro_final_necp_main_en_0.pdf

[9] Republic of Slovenia, "Integrated National Energy and Climate Plan of the Republic of Slovenia", 2020, https://energy.ec.europa.eu/system/files/2020-06/si_final_necp_main_en_0.pdf

[10] Ministry of Environment and Energy, "Integrated National Energy and Climate Plan for the Republic of Croatia for the period 2021-2030", 2019, https://energy.ec.europa.eu/system/files/2020-01/hr_final_necp_main_en_0.pdf

[11] Ministry of Mining and Energy, Ministry of Finance and Department for Controlling and Financing of EU Funded Programmes, "Integrated National Energy and Climate Plan of the Republic of Serbia until 2030 with a vision until 2050", 2022, https://www.mre.gov.rs/sites/default/files/2022/07/inecp_27_07_2022_eng.pdf

[12] Á. Beöthy et al., "SEERMAP: South East Europe Electricity Roadmap Country report: Serbia 2017", 2017, www.seermap.rekk.hu

[13] ENTSO-E, "European Power System 2040 – Completing the map – Technical Appendix", 2019, https://eepublicdownloads.entsoe.eu/clean-documents/tyndp-documents/TYNDP2018/european_power_system_2040.pdf

[14] Felice M de, "ENTSO-E PECD (European Climate Database) from MAF 2019 in CSV and Feather formats", 2020, doi:10.5281/ZENODO.3702418

[15] Energy Exemplar, "PLEXOS Guide", 2022

[16] Renewables.ninja, "Website", https://www.renewables.ninja/

[17] S. Pfenninger and I. Staffell, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," Energy, vol. 114, pp. 1251–1265, Nov. 2016, doi: 10.1016/J.ENERGY.2016.08.060.

[18] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," Energy, vol. 114, pp. 1224–1239, Nov. 2016, doi: 10.1016/J.ENERGY.2016.08.068.

[19] ENTSO-E. Mid-term Adequacy Forecast 2019 – dataset. 2019. https://www.entsoe.eu/outlooks/midterm

[20] J. Ho et al., "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020," 2021, www.nrel.gov/publications.

[21] Nuclear Energy Agency, "The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables", 2019, https://www.oecd-nea.org/jcms/pl_15000/the-costs-of-decarbonisation-system-costs-with-high-shares-of-nuclear-and-renewables?details=true

[22] Nuclear Energy Agency and International Energy Agency, "Projected Costs of Generating Electricity", 2020, https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf

[23] B. Biró and A. Aszódi, "Detailed numerical analysis of different energy scenarios and the role of nuclear energy in the decarbonization pathways of the Hungarian electricity system", 2022, European Nuclear Young Generation Forum 2021 - Book of Proceedings, pp. 131–134, doi: http://dx.doi.org/10.13140/RG.2.2.12641.38245

[24] European Commission. Delivering the European Green Deal. 2022. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en