# Assessment of Extending Operation of

# Nuclear Power Plant Krško from 2023 to

# 2043 – Techno economic, Ecological and

# Power Flow and System Dynamics InfluencE

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**Abstract**

The Krško Nuclear Power Plant - NEK, after almost 40 years of successful operation, is nearing the end of its originally assumed service life. The NEK is ready for an extension of its service life by another 20 years.

The assessment was performed to study the technical-economic and environmental impact of the operation of NEK, as well as the impact on the Croatian power system (taking into account the aspects of interaction between NEK and the operation of the Croatian power system) in the period between 2023 and 2043. In the analyses, two scenarios from the Croatian Energy Strategy were used to describe the future development of electricity generation in Croatia, and scenarios assumed rapid introduction of renewable energy sources.

Therefore, the lifetime extension of NEK proves to be economically more favourable. In addition to the economic aspects, extending the life of NEK is also more favourable from the environmental point of view, since extending the life of NEK means less CO2 emissions than the early decommissioning of NEK

The focus of the second part of the study is on the evaluation of the impact of the Krško NPP on the power flows and system dynamics in the Croatian power system. It deals with: Power flows and steady-state analysis of losses and voltages, as well as qualitative impact on system frequency dynamics of the simplified model of the isolated Croatian power system, with the aim of evaluating the impact of the NEK operation on the Croatian power system.

As can be seen from all analysed scenarios, cases and performed sensitivity analyses, the extension of the life of NEK proves to be the more favourable option in terms of economic indicators and greenhouse gas emissions.

The system with Krško NPP in operation has better synchronous inertia and dynamic response to disturbances.

## INTRODUCTION

The total installed capacity of the Krško nuclear power plant (NEK) is 696 MW and half of it is used for the Slovenian and half for the Croatian electricity grid. NEK is co-owned by the Slovenian state-owned company Gen Energija and the Croatian state-owned company Hrvatska elektroprivreda (HEP). NEK produces and supplies electrical energy exclusively for the benefit of the two shareholders in equal shares and operates on the principle of covering all costs without profit or loss [1]. The average annual energy produced is 5.7 TWh, of which one half covers about 20% of Slovenian electricity consumption and the other half about 16% of Croatian electricity consumption [2]. Commercial production in NEK started in 1983, and after almost 40 years of successful operation, NEK is about to extend its lifetime by another 20 years for the period 2023-2043

With the aim of planning the development of the energy sector in Croatia, taking into account the dynamic changes in the energy sector and international goals to increase the market penetration of renewable energy sources (RES), reduce greenhouse gas emissions and increase energy security and affordability, the Republic of Croatia adopted in 2020 a new Energy Development Strategy until 2030 with a view to 2050 [3]. In the wake of the EU Green Deal [4] and the EU vision for a climate neutral EU by 2050 presented in the Communication "A Clean Planet for All" [5], in 2020 the Republic of Croatia developed the scenario for achieving major emission reductions by 2030 and climate neutrality in the Republic of Croatia by 2050 for the energy sector [6] and in 2021 presented the scenario for achieving climate neutrality in Croatia by 2050 [7]. All national scenarios assume operation of NEK until 2043, and impacts are included without explicit quantification and recognition.

The aim of this work is to evaluate the techno-economic and environmental impacts of extending the operating life of NEK on the development of the Croatian electricity system. In doing so, the planned developments of the Croatian electricity system according to the S1 scenario presented in the National Energy Strategy [8] and according to the National Climate Neutral Scenario (SN) until 2050 [6] is simulated. For both scenarios, the impacts of cases with and without NEK lifetime extension are evaluated. The techno-economic impacts are quantified considering the impact on the required investments and the levelized cost of energy in the power system, while the environmental impacts are quantified considering the impact on greenhouse gas emissions in the power system. These simulations are performed by modelling the Croatian power system using the Plexos [9] modelling programme. Furthermore, from power system perspective, value of NEK Krško extension of life was assessed through different power system development scenarios using the PSS/e software.

The rest of the paper is organised as follows: in section 2 the methodological approach, scenarios and input data are presented, in section 3 the results are shown and discussed, and in section 4 the main conclusions are given.

## METHODOLOGICAL APPROACH AND INPUT DATA

### Techno-economic model

The techno-economic model used in this study refers to a series of linear programs (LP), e.g., one for each modelled day or week, and within each of these time steps there may be multiple problems, each with small differences, such as adding transmission constraints. These LPs are solved using the CPLEX 12.10.0.0 solver [10] to obtain high quality hourly results for a time horizon of 20 years.

In the first phase, a techno-economic model built in the Energy Exemplar PLEXOS® simulation software (hereafter: Plexos) [9] is used for the long-term analysis of capacity expansion - the analysis of existing generation capacity in the system and the analysis of capacity expansion in the power system, i.e., the analysis of investment in new capacity and the analysis of retirement of existing capacity. This phase minimizes the total net present value (NPV) of system costs over the long-term planning horizon (10-30 years). In this phase, the results of LCOE and total costs, installed capacity, and generation (and consumption) over time are determined at the level of the Croatian power system. In the second phase, the prospective system adequacy assessment (PASA) is performed to generate maintenance events for the subsequent simulation phases medium-term (MT) schedule and short-term (ST) schedule; to calculate reliability indicators such as the probability of load loss (LOLP). The data from the second phase will be used in the third phase. In the 3rd phase, the simulation MT (more than a week) is primarily for managing water storage, fuel supply, and emission constraints. The reason these medium-term constraints are so challenging is that the simulator must optimize decisions over weeks, months, and years while optimizing decisions at the short-term level (hour or lower). In the 4th and final phase, PLEXOS ST performs schedule optimization, i.e., short-term simulation (1 day to week) to obtain hourly dispatch schedules, pricing for real market clearing, unit commitment, constraint modelling, financial/portfolio optimization, Monte Carlo simulation, stochastic optimization. In the following sections, the main components of the techno-economic model are presented.

#### Generation

The heat-generating technologies under consideration are steam turbines and gas turbines, and steam power plants can run on oil, coal, or gas. Gas turbines require some form of gas - either natural gas or gas derived from coal or other sources. There are two main types of gas turbine plants: combined cycle (CCGT): a gas turbine generator produces electricity, and the waste heat is used to produce steam to generate further electricity via a steam turbine; this last step increases the efficiency of electricity generation. Open cycle (OCGT): here the gas turbine operates independently. Open cycle power plants are cheaper to build, but have lower efficiency than combined cycle power plants

Hydroelectric plants use the energy of water flow or the potential energy of stored water to offset thermal generation costs. The extent to which they can do this is determined by three factors: how much water the system can shop-the physical size of the reservoir; the timing of the precipitation: does it come all at once or slowly over time; the size and efficiency of the hydro turbines: how much they can produce at any given time.

Renewable energy sources (RES) wind and solar are modelled according to the predicted availability of wind and solar energy with hourly resolution. These generating units are intermittent, and their output is limited by the availability of wind and solar power. Capacity additions to these units are made in accordance with the specified scenarios. In order to maintain unsupplied energy at an acceptable level, these units require flexible generation and, in some cases, baseload generation at an acceptable level. Capacity additions to these units from geothermal and biomass are consistent with the modelled scenarios. These power plants are mostly considered as baseload power plants, but their installed capacity is rather limited.

Nuclear power capacity additions are in line with the modelled scenarios. Annual power generation is consistent with owner projections. This generation is considered baseload generation and is a firm capacity that improves long-term generation adequacy.

In this model, generators are assumed to be active sources of power, and generator models are subject to several technical constraints: startup cost and time, minimum startup and shutdown times, minimum stable level, ramp rate, short-run marginal cost, operation and maintenance cost, startup and shutdown cost, cost of supplying auxiliary loads to the generator, cost of debt and equity, etc. For new capacity expansion candidates, comprehensive characteristics are used: Construction cost, decommissioning cost, project start/end, technical/economic life, WACC, maximum/minimum number of units, etc. Generators have incremental costs per MWh based on three key factors: (1) cost of fuel consumed (fossil: gas, oil, coal; nuclear: uranium; renewable: hydro, wind, tidal, solar, etc.); (2) generation efficiency, which is determined by technology type; and (3) generator maintenance costs.

#### Load

In this study, the load is fixed and it is assumed that consumers will pay any price to meet their load. However, despite the fixed load, there are several flexibility options in generation and storage, such as battery energy storage systems (BESS) or thermal storage. In addition, it is assumed that there is a maximum price beyond which consumers prefer to be "turned off" rather than consume energy. This price is referred to as the Value of Lost Load (VoLL). Thus, if generation or other technical or transmission constraints mean that the entire load cannot be met, the unmet energy will make up the difference, and the market price will be equal to the VoLL (usually a high number such as € 10,000/MWh). If generation exceeds load, dump energy will make up the difference, and the market price will be set at the dump energy price (generally a number like -$1,000/MWh). To ensure the feasibility of the problem, unsupplied energy and dump energy must be accounted for in the simulations.

#### Transmission

In the technical-economic model defined for this study, AC, transmission system lines are modelled with impedances, i.e., line reactance and line resistance, and these lines are subject to Kirchkoff's Current Law (KCL) and Kirchkoff's Voltage Law (KVL).

#### Markets

The defined techno-economic model considers several markets that affect the performance of the power system, such as the electric power market, the emissions market (ETS), the fuel market, and the heat market. The electricity market defined here uses projected prices from the year 2020 to the year 2043 based on the scenario defined in Section 2.3

To model real-world situations, the price signals and incentives in the emissions, fuel, and heat segments of the electricity system are introduced. These markets are also based on the price forecasts for 2020 to 2043 based on the modelled scenarios.

#### Simulations

The techno-economic model in this study refers to a series of linear programmes (LP), e.g., one for each day or week, that are modelled, and within each of these time steps there may be several problems with small differences, such as adding transmission constraints. When a LP has been solved and then solved with modifications, it is often possible to start the LP solution algorithm from the last optimal solution. In this case, it is called a warm start or a hot start: a hot start occurs when only minor changes have been made, such as changing an objective function value or a right-hand side value, while a warm start involves all changes, including adding or deleting entire constraints. Warm or hot starts are always performed using the simplex method, and when the interior point method is executed, it is always augmented with simplex so that warm/hot starts can be performed [9]. Specifically, in this study, the techno-economic model is solved using the CPLEX solver

The simulations are performed using the techno-economic model for the time horizon from 2020 to 2050, and all the predicted data in the simulation are made in accordance with the reference values from the modelled scenarios

The study takes into account all important aspects defining the Croatian energy system, such as: imported electricity, long-term projections of electricity load, electricity prices, fuel prices and prices for CO2 emissions, water availability, intermittency of wind and solar energy, models of generation units and projections of installed capacity and generation growth in the Croatian energy mix according to the modelled scenarios. Discounting is also performed in accordance with the input data. Technical details of power plants, efficiencies, capacity factors, etc. are obtained from owners and/or taken directly from the modelled scenarios. Transmission costs and projections for additional transmission system investments are considered. Also considered are additional energy storage and transmission system investments needed to accommodate intermittent renewable energy sources (RES). Carbon capture and storage (CCS) is considered and is done in accordance with input data. Planned decommissioning of power units is implemented in accordance with input data. Decommissioning costs are considered and are in accordance with the owner's forecast NEK. Decommissioning costs of NEK are considered in both cases, i.e. for the case of early decommissioning in 2023 and decommissioning in 2043.

#### Limitations of the modelling approach

Generator models are not dynamic models and cannot analyse the dynamic characteristics (inertial response, frequency response, voltage and current time variation) of generators.

Transmission model: loads and generation in this model are connected through an equivalent high-voltage network (HV), i.e., all generators and loads are assumed to be connected to HV nodes and the nodes are interconnected through HV lines. Load and generation are expressed in terms of active power (MW of electricity).

Natural conditions - it is assumed that the average annual capacity factors for renewable energy sources are possible each year, which was an approach in the technical basis for the Energy Strategy of the Republic of Croatia. The annual potential for energy production may fluctuate, especially in the case of hydropower plants, and in the case of lower production it is usually compensated by other sources or imports. In the sensitivity analysis, the results are also tested for the change of some input data.

### Scenarios

In order to evaluate the energetic, economic and environmental impacts of the NEK Dispatch on the Republic of Croatia (RH) and the Croatian electricity system (EES) in the time horizon from 2020 to 2043, the assumptions of the Croatian Energy Development Strategy [3] are used. Two main cases were analysed: The first case is the operation of NEK until 2043 and the second case is the operation of NEK until 2023 and the subsequent replacement with the most competitive alternative energy sources.

These two cases are evaluated for two scenarios (Scenario 1 and Scenario SN), which have a great impact on the development of the Croatian power system:

* Scenario 1 (S1) is scenario of accelerated energy transition from Energy development strategy Of the Republic of Croatia by 2030 with a view to 2050 [3] [8] and,
* Scenario SN (SN) is a climate neutral scenario from report Climate neutral scenario of the Republic of Croatia [6].

The simulations are done using the techno-economic model for time horizon from 2020 till 2050 where all forecasted data in simulations are harmonized with reference values from S1 and SN scenarios.

### Input data

The main input data comes from the technical basis for the development of the energy strategy [8] and the technical basis for the development of the climate neutral scenario [6]. The study considers all important aspects defining the Croatian energy system, such as imported electricity, long-term projections of electricity load, electricity prices, fuel prices and prices for CO2 emissions, water availability, intermittency of wind and solar energy, models of generation units, and projections of installed capacity and generation growth in the Croatian electricity mix according to the S1 and SN scenarios. Technical details of the power plants, efficiencies, capacity factors, etc. were obtained from the owners and/or taken directly from the S1 and SN scenarios. Transmission costs and projections for additional transmission system investments are included as per S1 and SN. Additional energy storage and transmission system investments required to accommodate intermittent renewables (RES) are also considered. Carbon capture and storage (CCS) is considered in accordance with the SN scenario, as the SN scenario is the only scenario that envisions the deployment of CCS around 2040 for gas plants, which will only be in operation at conventional power plants at that time. The planned decommissioning of power plant units is in line with scenarios S1 and SN. Decommissioning costs from NEK are included and are consistent with the owner forecast from NEK. The decommissioning costs of NEK are considered in both cases, i.e. for the case of early decommissioning in 2023 and for the case of decommissioning in 2043, and they are the same. Decommissioning costs are nuclear expenses in both cases, but in this analysis they are paid by the owners and not by the plant. This means that in the case of early decommissioning NEK they should be paid from other resources of the owner, and in the case of extended operation they are paid by the owner from the difference between electricity production NEK and the market price. For another 20 years of operation, the collected amount is slightly less than 200 MEUR, and the same amount should come from other sources of the owner in case of early decommissioning NEK.

It should be mentioned that the Croatian Energy Strategy is based on the data of the document "EU Reference Scenario 2016 Energy, transport and GHG emissions" [11].

Some data have been supplemented with the latest information from NEK. Projected maintenance-related outages of NEK are scheduled in cycles of 18 months with a duration of 30 days. The revenue and expense projections for each scenario period were prepared as fixed prices based on January 2021 data obtained from NEK, so inflation or other price changes were not considered. The cost projection includes all cost categories from the business plan. The projected prices are between 28-33 EUR/MWh (30.5 on average) for the early shutdown of the power plant and between 23-31 EUR/MWh (29.0 EUR/MWh on average) for the expected extension of the plant's operation until 2043. All other future charges, taxes, etc., not included in the current legislation are not included in the cost projection (as they are not certain or known at the time of the analysis). The price of electricity is set according to the principles of the 2001 Agreement and the Certificate of Incorporation; the price should cover all costs, which means that there is no profit or loss. All profits accrue at the level of direct owners.

The total amount of investment work related to the Security Upgrade Program (SUP) [12] will be carried out between 2014 and 2021 and is not included in the analysis because it has already been spent and has no direct impact on the evaluation of the future operating options of NEK.

The average hourly wind electricity production in 2019-2020 was 182.0 MW with a maximum of 717.4 MW and a minimum of 2.4 MW. Average hourly solar power production in 2019-2020 was 8.3 MW with a maximum of 46 MW and a minimum of 0 MW. The same scaled solar availability is used throughout the analysis.

In addition to the listed data on the projected production and cost of NEK, the following key data from the technical basis of the energy strategy and the carbon-neutral scenario are used. Fuel costs, average electricity market prices, and CO2 allowance costs are shown in Table 1. The current EUA price is already higher than the assumed price (above 50 EUR/tCO2), and the price of emission allowances is expected to increase faster than assumed. Due to the assumed large share of RES power plants in the scenarios used, we do not expect a large impact on the results/conclusions.

Table 1: Costs of fuels, electricity and CO2 allowances [8]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Item | 2020. | 2030. | 2040. | 2050. |
| Market electricity price (EUR/MWh) | 40.6 | 60.0 | 77.3 | 83.7 |
| CO2 allowances price (EUR/tCO2) | 25.6 | 34.3 | 51.1 | 92.0 |
| Price of coal (USD/t) | 63 | 80 | 82 | 84 |
| Price of natural gas (USD/GJ) | 6.45 | 8.15 | 9.1 | 10.05 |

The assumed discount rate was 8%, as in the Green Paper on Energy Strategy. Furthermore, the costs of the technologies were integrated into the model, based on the same source [8].

The possible maximum capacity factors were also taken from the Green Book on Energy Strategy, while projections of hourly production curves were used for variable renewable energy sources such as solar and wind.

Transmission costs, grid infrastructure, and other external costs associated with grid expansion were included in this analysis. Based on the costs reported in Scenario S1 and Scenario SN, the additional cost of grid infrastructure investment per MW of variable renewable energy sources (wind and solar) is included in the optimization of newly installed capacity for the case without NEK after 2023, which is about 8 EUR/MWh, which is in the range of the IEA assessment of 2-10 USD/MWh. In addition, a total of 400 MW battery energy systems are envisaged by 2050 in the S1 scenario and 1200 MW by 2050 in the SN scenario. Linear growth is assumed in the model. Real costs in 2020 prices are used to determine the LCOE. The LCOE are given in 2020.

## RESULTS AND DISCUSSION

In this section, a comparative analysis of the scenarios is presented, including the main indicators for evaluating investments and details of the power system for the analysed time horizon from 2020 to 2043, including: installed capacities, generation, CO2 emissions, annualised power generation costs, total costs, and system LCOE for the analysed time horizon from 2020 to 2043. A techno-economic model was created to evaluate the interaction between the power system and NEK in the case of decommissioning in 2023 and extended operation until 2043. It also examines which alternative energy sources, such as wind, solar, biomass, geothermal, gas, coal, and hydropower, or energy imports, can most cost-effectively replace NEK if NEK is decommissioned, keeping in mind that the replacements should be equivalent in terms of energy. All of this is done for scenarios S1 and SN. Carbon capture and storage (CCS) is considered in accordance with the SN scenario, since the SN scenario is the only strategy scenario in which CCS is expected to be used. CCS is assumed to be applied to gas plants in 2040, which will be the only conventionally-fueled power plants in operation at that time.

Simulations are performed with forecasted data (electricity prices, fuel prices, load values) based on the S1 scenario. In addition, the annual generation volumes of all power plants in the simulation are adjusted to the values of the S1 and SN scenarios. The simulation is performed for a time horizon of 31 years (from 1/1/2020. to 12/ 31/2050) with an hourly resolution. This is done for four simulation phases: 1st phase: long term plan for expansion planning, 2nd phase: PASA to calculate system adequacy, 3rd phase: to decompose long term boundary conditions and create weekly set points; 4th phase: optimal hourly dispatch considering power plant boundary conditions, ramp rates, heat rates and other technical and economic characteristics.

### Energy and GHG emissions

The impact of NEK early retirement in 2023 on the overall mix of installed capacity in the Croatian power system was examined. The summary results of total installed capacity are shown in Figure 1 and total generated electricity in Figure 2 - for the two scenarios analysed, each of which includes two cases.

The results show that the most favourable replacement technologies for NEK in the case of its early decommissioning in 2023 are wind power plants and photovoltaic plants. The replacement of NEK as a baseload power plant was carried out in terms of generated energy. The additional cost of developing and operating the power grid due to the introduction of RES (depending on the share) was taken into account. The planned storage capacity in the system ranges from 50 MW in 2023 to 250 MW in 2043 (storage capacity from 65 to 320 MWh) in the S1 scenario. This is the energy storage required for the successful operation of the system with the given RES fractions. It is not only used for replacement of production from NEK. Replacement of power plants with high capacity factor is provided in average weather conditions based on the surplus RES power plant capacity and its diversity (hydro, wind and photovoltaic), participation of other power plants in the system and to some extent use of energy storage. The simulation results in the S1 scenario show that the early closure of NEK in 2023 means that NEK should be replaced by solar power plants with an installed capacity of 750 MW, whose commissioning should start in 2031 (250 MW in 2031, 250 MW in 2032, and 250 MW in 2033). In addition, NEK is replaced by wind power plants with an installed capacity of 750 MW, whose commissioning should start around 2030 (300 MW in 2030, 300 MW in 2031, and 150 MW in 2032). The simulation results in the SN scenario show that the early retirement of NEK in 2023 in the SN scenario means that NEK should be replaced by solar power plants with an annual construction distribution of 250 MW in 2031, 250 in 2032, and 250 in 2033. Also NEK is replaced by wind power plants starting commissioning around 2030, with a construction schedule of 300 MW in 2030, 300 MW in 2031 and 150 MW in 2032. The timing of commissioning is fully determined by the optimization procedure in the first phase of the Plexos solution procedure to minimise the net present value of the total system. The study of the impact of the early decommissioning of NEK in 2023 on the overall mix of installed capacity in the Croatian power system shows that due to the lower capacity factors of alternative power plants (solar and wind) that replace NEK in terms of energy (they must generate the same amount of energy as NEK over the entire simulation horizon), a much higher installed capacity is required (Figure 1). This increase in capacity is clearly visible in 2030 and later when new wind and solar are added. It is important to note that the simulation results of the techno-economic model show that if NEK is retired early in 2023, the new alternative solar and wind plants could be less economically disadvantageous than electricity imports prior to 2030, meaning that the early retirement of NEK in 2023 could have negative impacts on generation adequacy, system reliability, and stability from 2023 to 2030.

Figure 1: Comparison of installed capacity in analysed cases

Figure 2: Comparison of produced electricity in analysed cases

Figure 3 shows the time-dependent CO2 emissions for cases with and without NEK lifetime extension. The environmental benefits of extended operation of NEK can be clearly seen, as the Croatian environment is relieved by 11,193 ktCO2 in the period from 2023 to 2043 in the S1 scenario. This is mainly due to the lower CO2 emissions from the gas units in case of NEK life extension. If NEK is retired in 2023 and replaced by solar and wind power, this means that more gas-fired power plants, which are peaking power plants, will be used to compensate for unavailable wind and solar generation during certain hours. In percentage terms, extending the life of NEK means a 21.3% reduction in CO2 impact. It should be noted that the EUA price used for the calculation was taken from the strategy. The current EUA price is over 50 EUR/tCO2. In simple terms, this means that in the event of an early shutdown of NEK, we could see an additional price increase due to increased emissions of up to EUR 300 million. There is no immediate increase in CO2 emissions because time is needed to build new power plants after NEK is shut down. During this time, imports must be resorted to cover the demand.

In the SN scenario, the environmental aspect of operating from NEK to 2043 is beneficial, as 2,024 ktCO2 less are emitted in the period from 2023 to 2043. This is mainly due to the lower production of gas units in case of extension of NEK operation. If NEK is retired in 2023 and replaced by solar and wind power, this means that more gas-fired power plants, which serve as peaking power plants, will be used to offset unavailable wind and solar generation during certain hours. In percentage terms, extending the lifetime of NEK for the SN strategy scenario means a 4.7% lower CO2 impact in Croatia. Compared to scenario S1, CO2 emissions in scenario SN decrease significantly in the second half of the diagram, which is due to the introduction of CCS technologies from 2035, as foreseen in scenario SN.

Chart, line chart

Description automatically generated

Figure 3: Comparison of CO2 emissions in analyzed cases

Figure 4 shows the total annual system cost for both scenarios (S1 and SN) and both cases (NEK operation until 2043 and NEK early retirement in 2023). This graph shows that operation from NEK to 2043 means lower total system costs for the Croatian power system from 2023 to 2043. Compared to the early retirement of NEK, the operation of NEK until 2043 is a more cost-effective solution for Croatia and the Croatian power system as a whole, as the total system cost is 7.4% lower in the S1 scenario, which in absolute terms means an undiscounted saving of EUR 2.15 billion for the Croatian power system as a whole. In the SN scenario, operating from NEK to 2043 means a 5.9% reduction in total system costs, which in absolute terms means undiscounted savings of EUR 2.247 billion.

Figure 4: Total yearly system costs

Figure 5 and Table 2 show the total annual system cost of the Croatian electricity system divided by the annual electricity generation, i.e., the system-related energy cost in €/MWh. The average cost of electricity in the case of operating NEK until 2043 is about 7% lower than in the case of early shutdown in the S1 scenario. This cost reduction by operating NEK until 2043 undoubtedly means that electricity becomes cheaper on the Croatian wholesale electricity market and Croatian consumers receive cheaper electricity. A similar trend is also observed in the SN scenario.

Figure 5: Comparison of Annualized electricity production costs in analyzed cases

TABLE 2: Yearly system levelized costs for the analyzed scenarios and cases in the period 2020 – 2043 (EUR/MWh)

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario and case | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 |
| S1\_NEK2043 | 48.4 | 49.6 | 51.0 | 51.0 | 52.4 | 55.2 | 56.1 | 57.4 | 58.5 | 59.0 | 62.3 | 62.9 |
| S1\_NEK2023 +alternative | 48.4 | 49.6 | 51.0 | 52.5 | 53.8 | 56.7 | 58.3 | 59.7 | 61.2 | 62.5 | 66.1 | 68.0 |
| SN\_NEK2043 | 48.4 | 51.3 | 53.5 | 54.0 | 56.1 | 57.1 | 58.1 | 59.4 | 60.1 | 61.0 | 61.9 | 62.8 |
| SN\_NEK2023 +alternative | 48.4 | 51.3 | 53.5 | 55.4 | 57.2 | 58.4 | 60.2 | 61.3 | 62.3 | 64.2 | 67.2 | 67.8 |
| Scenario and case | **2032** | **2033** | **2034** | **2035** | **2036** | **2037** | **2038** | **2039** | **2040** | **2041** | **2042** | **2043** |
| S1\_NEK2043 | 61.1 | 60.0 | 58.5 | 58.3 | 54.0 | 53.5 | 52.9 | 52.3 | 53.2 | 53.4 | 52.4 | 52.1 |
| S1\_NEK2023 +alternative | 67.5 | 66.6 | 65.0 | 64.9 | 60.3 | 59.9 | 59.5 | 59.0 | 59.5 | 60.1 | 58.4 | 57.9 |
| SN\_NEK2043 | 61.4 | 60.5 | 59.6 | 60.2 | 57.2 | 56.7 | 55.1 | 55.0 | 55.9 | 55.3 | 55.6 | 55.2 |
| SN\_NEK2023 +alternative | 69.3 | 67.6 | 66.6 | 65.6 | 62.0 | 61.5 | 60.2 | 59.7 | 60.5 | 60.5 | 60.2 | 59.8 |

Summary results on the system's electricity production costs are shown in Table 3 and Figure 6. A further summary of total costs and CO2 emissions can be found in Table 3. The main results can be summarized as follows:

* The S1 scenario shows that extending operation from NEK to 2043 results in a reduction in system LCOE of EUR 3.14/MWh, or 5.4%, and a reduction in total system costs of EUR 2.149 billion (7.4%). EUR (7.4%) compared to the case without the lifetime extension of NEK. Therefore, extending the life of NEK proves to be more economically beneficial. In addition to the economic aspects, extending the life of NEK is also more beneficial from an environmental point of view, as extending the life of NEK means 21.3% less CO2 emissions compared to the early retirement of NEK.
* These conclusions can be repeated for the scenario SN, where the extension of operation from NEK to 2043 results in a reduction of the system LCOE by 3.05 EUR/MWh or 5.1% and a reduction of the total system cost by 2.247 bn. EUR (5.9%) compared to cases without NEK lifetime extension. Thus, extending the life of NEK proves to be more economically beneficial even in the SN scenario. In addition, extending the life of NEK also leads to a reduction in CO2 emissions in this scenario, but to a lesser extent (4.7%), as CO2 emissions have already decreased in this scenario due to the ambitious targets and increased installation of renewable energy sources and batteries, as well as CCS technology for natural gas power plants, leaving less room for a small increase in the case of earlier decommissioning of NEK (a non-CO2 power source).

TABLE 3: Comparison of the main system indicators for the period 2020 – 2043

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario and case | LCOE  (EUR/MWh) | Total system costs  (bln. EUR) | Total CO2 emissions  (kt CO2) |
| S1\_NEK2043 | 54.71 | 26.978 | 41,413 |
| S1\_NEK2023+alternative | 57.85 | 29.128 | 52,606 |
| *Difference* | ***-3.14 (-5.4 %)*** | ***-2.149 (-7.4 %)*** | ***-11,193 (-21.3 %)*** |
| SN\_NEK2043 | 56.81 | 35,584 | 40,993 |
| SN\_NEK2023+alternative | 59.86 | 37,832 | 43,017 |
| *Difference* | ***-3.05 (-5.1 %)*** | ***-2.248 (-5.9 %)*** | ***-2,024 (-4.7 %)*** |

Figure 6: Comparison of system LCOE in the analyzed scenarios and cases

### Sensitivity analysis

For scenario S1, the effects of different discount rates and electricity prices on the total cost of the system are shown in Figure 7. It can be observed that changes in import prices have a relatively smaller impact on the S1 scenario, especially when operating from NEK to 2043, since it is a scenario that represents the results of the energy strategy, where net imports decrease. The impact of different discount rates is more significant because it directly affects the feasibility of new investments and the changes in total and levelized system costs that occur over the time horizon considered.

In the sensitivity analysis of the impact of 5% higher market prices in the case of NEK early retirement in 2023, higher market prices lead to higher system costs by 2033. In the period 2034-2043, system costs are lower than in the base case due to investments in new capacity and increased exports. These offsetting effects lead to a slight decrease in system LCOE over the 2020-2043 time horizon considered.

In the sensitivity analysis with a lower discount rate of 2%, there is a significant decrease in system-related costs over the 2020-2043 period for both cases-with NEK operating until 2043 and for a case with shorter NEK operating until 2023. This is due to the fact that lower discount rates lead to lower annualized investment costs and more competitive domestic power generation. This led to a decrease in total system costs from 54.7 EUR/kWh to 49.9 EUR/kWh (by 8.8%) in the case of extended NEK operation and from 57.8 to 52.3 EUR/kWh (by 9.5%) for the case of earlier decommissioning NEK

On the other hand, increasing the discount rate from 8% to 10% has an opposite effect on the levelized system cost, and there is an increase in the annual levelized system cost. This is because a higher discount rate discourages investment in RES and in domestic generation (since electricity prices are assumed to remain at the relatively low level equivalent to the base case). This led to an increase in the system LCOE from 54.7 EUR/kWh to 56.9 EUR/kWh (by 4.0%) in the case of extended operation of NEK and from 57.8 to 58.6 EUR/kWh (by 1.4%) for the case of earlier closure of NEK.

The results of the sensitivity analysis for the SN scenario show that a 5% increase in import prices has a relatively smaller impact than changes in discount rates from 8% to 2% and 10%.

In the sensitivity analysis of the impact of 5% higher market prices in the 2023 case of NEK early retirement, higher market prices lead to higher system costs by 2030. In the 2031-2034 period, annual system costs are lower than in the base case due to more competitive domestic production and lower imports. In both cases, these effects lead to a slight decrease in total system costs over the 2020-2043 time horizon considered.

In the sensitivity analysis for a lower discount rate of 2%, there is a significant decrease in system-related costs over the 2020-2043 period for both cases-with NEK operating until 2043 and for the case with shorter NEK operating until 2023. This is due to the fact that lower discount rates lead to lower annualized investment costs and more competitive power generation. This led to a decrease in the system LCOE from 56.8 EUR/kWh to 52.9 EUR/kWh (by 6.9%) in the case of extended NEK operation and from 59.9 to 55.5 EUR/kWh (by 7.3%) for the case of earlier decommissioning NEK

On the other hand, the increase of the discount rate from 8% to 10% has an opposite effect on the levelized system cost, and there is an increase in the annual levelized system cost. The exception is the case with NEK early retirement and in the 2030-2033 period, where the annual system cost decreases relative to the base case as investment in new capacity is deferred. However, this deferral translates into higher costs later. The increased discount rate discourages investment in RES as potential new domestic generation becomes more expensive (as market prices for electricity are assumed to remain at the relatively low level equivalent to the base case). Overall, this led to an increase in the system LCOE from 56.8 EUR/kWh to 58.8 EUR/kWh (by 3.5%) in the case of extended operation of NEK and from 59.9 to 60.2 EUR/kWh (by 0.5%) for the case of earlier closure of NEK.

### Power flows perspective

Taking into account installed capacity of Croatian power system, its interconnections to neighbouring power systems and share of the Croatian part of NPP Krško production, overall influence of NPP Krško operation owned by Croatian company is not detrimental. Still, taking into account characteristics of NPP Krško production and its position within the power system, extended operation of NPP Krško is beneficial for Croatian power system in every way. Due to load located in northern part of the country and due to replacement sources located in south part of the country (mostly wind and solar) and taking into account configuration of the grid, more uniform load of the system and less power loss is expected for NPP Krško in operation than without it. That was demonstrated for one characteristic load sequence (high load and rather favourable conditions for RES energy production).. All analyses were performed for average meteorological situation and for normal availability of fossil fuels and elements of power system. Thanks to independence on the fuel supply (at least on the time scale of one year) and independence on natural and weather resources and taking into account robust design and proven high reliability, NPP Krško has additional benefits, not covered in this study, compared to any replacement source.

All the analysis conducted are in accordance with the most recent 10 year development plans (10G) of the Croatian transmission system operator (TSO) HOPS, mainly in regard to the grid development and new production capacity integration, and ENTSO (European Network of Transmission System Operators) 10-year development plan (TYDP):

- 10 year development plan of the Croatian TSO for the period from 2021-2030 [13],

- 10 year development plans of ENTSO-e (TYDP) [14], [15], [16].

The power system model is developed in PSS/E software package and consists of:

• Detailed model of the 400 kV and 220 kV network of the Continental Europe

• More detailed 110 kV networks of neighboring systems: BiH, Slovenia, Hungary and Serbia.

• Detailed 110 kV network of the Croatian electric power system (EPS) with some of the more important 35 kV lines considered.

In summary, this section briefly described the general complexity of the used power system model for power flow studies, most relevant HV transmission lines in Croatia with regards to the location of NPP Krško, considered FACTS devices in Croatia and Slovenia and the type of generator nodes (PV/PQ). The final power grid model consists of (approximately): 13000 buses, 2500 generators, 6400 loads, 16000 lines, 2600 transformers on the whole European level and 7 FACTS devices specifically oriented on Croatian system and its surrounding.

For the purpose of evaluating the impact of NEK Krško, the assumed power system development direction was needed to allow the integration of additional capacities of wind and solar required to replace NPP Krško power. The assumed power system layout is shown on Figure 7. Into different power system development stages exact projects with their exact location were fitted. These have been integrated into the final model with their respective exact grid location and grid connection scheme accounting for the necessary grid strengthening investments. It also needs to be noted that there is a large dose of uncertainty associated even with this list of selected projects and this is prone to changes depending on different political, financing, social and project development impacts, but for the purposes of conducted analysis the important segment was covered to replace and maku-up for the NEK Krško capacity in case it does not get the lifetime extension.



Figure 7: Configuration of 400 kV and 220 kV networks around year 2033

Further assumptions:

- In all the scenarios NPP Krško is regarded to be operational at its output power of around 700 MW;

- All the scenarios are observed for a high demand/peak power consumption case;

- Demand was scaled on the existing consumption points (185 consumption points on 110 kV voltage level) to accommodate the expected growth in the coming 20+ year horizon (2023 to 2043);

- Distributed generation (including biomass) on the DSO level (35 kV voltage level and lower, installed capacity 5 MW or smaller) was considered through addition of generation adjacent to the demand buses in a total sum from 75 MW to 500 MW as the time horizon progresses because of the expected increase through the years;

- NPP Krško power production that needs to be substituted in the case NEK Krško early shutdown is replaced by the approximately proportional mix of wind, solar and hydro;

- New production units are added in accordance with exact locations of the realistic potential projects and with their exact discrete power;

- Battery storage is added on the exact planned locations in the simulated year case-study in accordance to the grid connection. The storage is not having any detrimental role in the steady state analysis;

- Current coal fired power plants were phased out according to current operational plan and no new coal investments were considered.

- Geothermal power plants were added in their exact planned locations in the northern and eastern regions of Croatia;

- Gas powered power plants are maintained on the current locations with new additions that sum up to the energy mix according to development Strategy;

- All already constructed hydro power plants are kept operational with new ones added on their exact locations and with their discrete power;

- Solar and wind projects were added respective of total installed capacity in the predicted energy mix in accordance to the Strategy;

- Production balances of neighbouring systems are kept fixed on the levels of period 2020-2023;

- N-1 analysis was not performed;

- The coincidence factors (Table 4) of wind, solar and hydro are based on expected hour and month of high load occurrence. They are based on the connection scenarios of Croatian TSO HOPS. Coincidence factor determines the shares of installed capacity of the respective generation type that is online for the snapshot of the power flow case. The coincidence factors used for the high load and medium-to-high production are based on analysis of historical data. In the total yearly hours this scenario is approximately represented in 20% of times specifically during mid-day peaks and spring-summer-autumn late afternoon peaks. This scenario was selected to be the representative since in the hours they occur they take up a large share of total energy usage.

TABLE 4: Coincidence factors for different production types in the analysed study-cases

|  |  |  |  |
| --- | --- | --- | --- |
| SCENARIO | HPP  [% OF TOTAL POWER] | WPP [% OF TOTAL POWER] | SPP [% OF TOTAL POWER] |
| 2020 | 55 | 60 | 100 |
| 2023 | 55 | 60 | 100 |
| 2033 | 55 | 60 | 100 |
| 2043 | 55 | 60 | 100 |

An example of comparison of power flows is shown on Figure 8.



Figure 8: Representative power flows, for case-study with NEK (left) and without NEK substituted by alternative sources, in 2033 – “b\_2033” (right)

What can be observed in all study-cases is that the substitution of NPP Krško with new generation units, mostly wind and solar, which are anticipated to be located in the southern parts of Croatia, increases the average system loadings and increases system losses for simulated grid conditions. That is so due to favourable location of NPP Krško close to consumption centres in the northern parts of Croatia. That part of the country is not expected to experience large penetration of wind and solar RES.

### Power system dynamics analysis

Thanks to its inherent stored kinetic energy, operation of NPP Krško is better from point of view of system stability giving lower frequency drop and lower rate of initial frequency change in case of power production imbalance. Croatian electric power system is relatively small, and it is well-interconnected with the rest of the European interconnection, thus impact of any one power plant on bulk power system dynamics should be small. That is especially true from frequency dynamics and system inertia point of view. Nevertheless, the share of non-synchronously connected renewable energy sources is increasing and will continue to increase in most European countries. Therefore, reduction of the grid inertia is expected continent-wide, and research indicates that it will become heterogeneous: time-variant and spatially distributed depending on the weather conditions. Inertia is an important characteristic of an electric power system which describes its resistance to load-generation mismatch and is closely related to frequency stability.

To assess the impact of nuclear power plant (NPP) Krško on the inertia and frequency dynamics of the Croatian electric power system, the Croatian electric power system is observed in island mode using available power plant data including NPP Krško. It is clear that in island mode the impact of any disturbance will be overestimated. Due to its geographic characteristics, it can be divided into north and south areas. Based on Croatian electric power system development plans and long-term forecasts which include decommissioning of existing thermal power plants and installation of new capacities, the evolution of the Croatian grid inertia in terms of rotational kinetic energy is estimated with (label NEK2043) and without (label NEK2023) NPP Krško in figures below (Figure 9). NPP Krško is included in the north region of the Croatian electric power system. Decommissioning of NPP Krško significantly reduces the kinetic energy of the north region (around 37%) and the total system kinetic energy around 25% for the year 2025 compared to the situation when NPP Krško stays online until the year 2043. In the year 2025 with NPP Krško in operation, rotational kinetic energy of the north region is reduced only 4% and total system kinetic energy is reduced 2%. Note that kinetic energy of the north region (Figure 10) and system in general is decreasing because all the thermal units scheduled for decommission are located there. On the other hand, synchronous kinetic energy of the south region (Figure 10) is expected to somewhat increase in the future due to new large synchronous hydro capacities planned for commissioning.

Chart, bar chart

Description automatically generated

Figure 9: Total kinetic energy of the Croatian electric power system including NEK Krško in operation until 2023 and for a case its in operation until 2043

Chart, bar chart

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Figure 10: Total kinetic energy of the Croatian electric power system in North (left) and south (right) regions

## CONCLUSION

After almost 40 years of successful operation, the Krško NPP is nearing the end of its originally assumed service life. Thanks to proper maintenance, planning and investment, including replacement and upgrading of old equipment and improvement of safety systems, the Krško NPP is ready for an extension of its life by another 20 years. The development plans of both Croatia and Slovenia were based on the assumption of extending the life of the plant. Recently, it has been recognized that an Environmental Impact Assessment (EIA) is required to address the extension of the plant's life. This study was prepared to compare the techno-economic and environmental aspects of extended operation of NEK with shutting down the power plant and replacing its production with the lowest cost energy sources (in this case RES).

This study is based on the data and assumptions of the Croatian Energy Strategy, which was adopted in 2020. In the meantime, some important inputs have been changed. This is mainly related to the increase in the prices of fossil fuels, raw materials and electricity, as well as the increase in the EUA price. These changes have a quantitative impact (e.g., using the current EUA price may increase the cost of replacing NEK by EUR 300 million in the case of S1) on the results of this study, in the sense that the extended operation of NEK is still cheaper, but they do not affect the conclusions of this study.

As it can be seen from all analyzed scenarios, cases and performed sensitivity analyzes, extending the life of NEK proves to be a more favourable option in terms of economic indicators and GHG emissions. Also for steady state power flows NEK Krško reduces the total network loses and reduces the average loading of vital 400 kV transmission lines. Finally, keeping NEK Krško in operation has a positive impact on total system inertia.

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