Techno-economic and Environmental Impact of NPP Krško Lifetime Extension on Croatian Power System Development

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ABSTRACT

Half of the 696 MW of total capacity of the Nuclear Power Plant Krško (NEK) is used for the Croatian power system, and energy generated for Croatia equalled 16.8% of final electricity consumption in Croatia in 2020. After almost 40 years of successful operation, NEK is nearing the lifetime extension for another 20 years for the period 2023-2043. In this paper, we assess the techno-economic and environmental implications of lifetime extension for Croatia. We simulate future developments of the Croatian power system in line with the S1 scenario presented in the national Energy Strategy, and in line with the national Climate-neutral Scenario until 2050. For both scenarios, we assess the implication of cases with and without NEK lifetime extension. Techno-economic implications are evaluated based on the additional investments needed and levelized cost of energy in the power system, while environmental implications are evaluated based on the impacts on emissions of greenhouse gases in the power system. The results point out that the lifetime extension of NEK proves to be economically and environmentally favourable. Moreover, in case of earlier retirement in 2022, the national power system and the economy would be exposed to a bigger risk of market prices and uncertainties (electricity, fuels, emission allowances) in the coming years, as no alternative solution can be built immediately.

Keywords: *nuclear power plant, greenhouse gas emissions, levelized cost of energy, power system, planning, optimization*

1 INTRODUCTION

Total installed capacity of Nuclear Power Plant Krško (NEK) is 696 MW and half is used the Slovenian and half for the Croatian power system. 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 in favour of the two shareholders in equal shares and it operates on the basis of the principle of covering all costs without profit or loss [1]. The average yearly energy generated equals 5.7 TWh, out of which one half covers about 20% of Slovenia's electrical energy consumption and other half about 16% of Croatia's electrical energy consumption [2]. Commercial production in NEK stared in 1983 and after almost 40 years of successful operation, NEK is nearing the lifetime extension for another 20 years for the period 2023-2043.

With an aim to plan development of the energy sector in Croatia considering the dynamic changes in energy sector amid the international goals for increasing penetration of renewable energy sources (RES), reduction of greenhouse gas (GHG) emissions, and increase of energy security and affordability, Republic of Croatia in 2020 adopted the new Energy Development Strategy until 2030 with a view to 2050 [3]. Further, in the wake of EU Green Deal [4] and the EU's vision for a climate-neutral EU until 2050 that was presented in A Clean Planet for all communication [5], Republic of

Croatia in 2020 developed the Scenario for achieving greater 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 until 2050 [7]. All national scenarios assume operation of NEK until 2043 and effects are included without explicit quantification and recognition.

The goal of this work is to assess the techno-economic and environmental implications of lifetime extension of NEK on Croatian power system development. In doing so, we simulate planned developments of the Croatian power system in line with the S1 scenario presented in the national Energy Strategy [8], and in line with the national Climate-neutral Scenario (SN) until 2050 [6]. For both scenarios, we assess the implication of cases with and without NEK lifetime extension. Techno-economic implications are quantified considering the impacts on investments needed and levelized cost of energy in the power system, while environmental implications are quantified considering the impacts on emissions of greenhouse gases in the power system. The simulations are conducted by modelling of the Croatian power system using Plexos modelling tool [9].

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

2 METHODOLOGICAL APPROACH AND INPUT DATA

In this Section we present the developed techno-economic model, scenarios and input data for the conducted simulations.

2.1 Techno-economic model

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

To get hourly dispatch for such a long period of time and to have a relative gap[1] of 0.01 % the problem is divided into four phases. In the 1st phase techno-economic model crated in Energy Exemplar Plexos® Simulation Software (hereinafter: Plexos) [9] is used for long-term analysis of capacity expansion. It is the analysis of the existing generation capacity in the system, and the analysis of capacity expansion in the power system, i.e. the analysis of investments in new capacities and the analysis of decommissioning of existing capacities. This phase minimizes the total net present value (NPV) of system costs over the long-term planning horizon (10-30 years). This phase is used to obtain the results of levelized cost of electricity (LCOE) and total costs, installed capacities and generation (and consumption) over time at the level of the Croatian electric power system. In the 2nd phase the projected assessment of system adequacy (PASA) is done to create maintenance events for the subsequent simulation phases mid-term (MT) schedule and short-term (ST) schedule; to compute reliability indicator such as loss of load probability (LOLP). The data from the 2nd phase are used in the 3rd phase. In the 3rd phase the MT simulation (more than one week) is done primarily for managing hydro storages, fuel supply and emission constraints. The reason that these medium-term constraints create such a challenge is because they imply that the simulator must optimize decisions spanning weeks, months and years, and simultaneously optimize decisions in the short-term (hour or lower) level. In the 4th the final phase Plexos conducts ST schedule optimization i.e., short-term simulation (1 day to week) to obtain hourly dispatch plans, pricing of real market-clearing, unit commitment, constraint modelling, financial/portfolio optimization, Monte Carlo simulation, stochastic optimization. In the following sections main components of techno-economic model are presented.

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[1] Relative gap or relative duality gap is a measure of how close is primal problem suboptimal solution to the optimal solution of dual problem. In other words, it is a measure of how close are we to the optimal solution.

2.1.1 Generation

The observed thermal generation technologies are steam turbine and gas turbine, where steam plants can run on oil, coal, or gas. Gas turbines require some form of gas - either natural gas or gas produced from coal or other sources. Gas turbine plants come in two main types: combined cycle (CCGT): a gas turbine generator generates electricity, and the waste heat is used to make steam to generate additional electricity via a steam turbine; this last step enhances the efficiency of electricity generation. Open-cycle (OCGT): here the gas turbine operates independently. Open-cycle plants are cheaper to construct but are less efficient than combined-cycle plants.

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

Productions from wind and sun are modeled according to the forecasted availability of wind and sun energy with hourly resolution. These generation units are intermittent, and their rating or power output is limited by availability of wind and sun energy. The capacity increase of these units is done in accordance with given scenarios. To have unserved energy within acceptable level these units need flexible generation and in some cases baseload generation in acceptable levels. Geothermal and biomass capacity increase of these units is done in accordance with the modelled scenarios. This power generation is considered mostly as a baseload, but their installed power is rather limited.

Nuclear generation capacity is done in accordance with the modelled scenarios. Yearly energy production is in line with owner’s projections. This power generation is considered a baseload generation and is firm capacity which improves the long-term generation adequacy.

The model assumes the generators as the active power sources where models of generators are subject to several technical constraints: start cost and time; minimum up and down times; min stable level; ramp rate; short-run marginal cost; operations and maintenance (O&M) costs; cost of startup and shut down; cost of powering the generator auxiliary loads; cost of debt and equity; etc. For new candidates for expansion capacity extensive features are used: build cost; retirements cost; project start/end date; technical/economical life; weighted average cost of capital (WACC); max/min units build etc. Generators have an incremental cost per MWh based on three key factors: (1) cost of the fuel (fossil: gas, oil, coal; nuclear: uranium; renewable: hydro, wind, tidal, solar, etc) being consumed; (2) efficiency of generation, which is determined by the technology type; and (3) cost of generator maintenance.

2.1.2 Load

In this study load is fixed and it is assumed that consumers will pay any price to meet their load. However, despite load being fixed, there are several flexibility options in generation and storage, such as battery energy storage systems (BESSs) or thermal storage. Also, it is assumed there is a maximum price above which consumers prefer being ‘switched off’ than to use energy. This price is called value of lost load (VoLL). Thus, if generation or other technical or transmission constraints means the all the load cannot be met, unserved energy will make up the difference, and the market price will be VoLL (usually a high number like 10,000 €/MWh). Likewise, if generation is forced higher than the load, dump energy compensates, and the market price is set to the price of dump energy (generally a number like -1,000$/MWh). Allowing for unserved energy and dump energy in simulations is a necessity in order to ensure feasibility of problem.

2.1.3 Transmission

In techno-economic model defined for the purpose of this study AC lines in the transmission network are modelled with impedances i.e. with the line reactance and resistance and these lines are subject to Kirchkoff's Current Law (KCL) and Kirchkoff's Voltage Law (KVL). This model assumes transmission can carry only the real power flow which is a subject of variable shift optimal power flow (VS-OPF) method for power flow calculation. Lines are defined with various number of technical constraints and parameters: min/max flow; resistance/reactance/susceptance; max ramp up/down; losses; fixed operating & maintenance (FO&M) charge; technical/economic life; WACC; maintenance rate/frequency; forced outage rate (FOR) etc. The VS-OPF linear programming formulation for optimal power flow is used. VS-OPF is a variation of the linearized direct current optimal power flow (DC-OPF) in which congestion and losses are modeled explicitly with nodal energy balancing constraints rather than with a fixed set of shift factors. Using a node-by-node energy balance means a more accurate representation of AC network losses because the power losses are 'lost' at the transmission lines ends and not at the nominated slack bus. Optimal power flow (OPF) refers to a generator dispatch and resulting AC power flows that result in is minimum production cost and are feasible considering the thermal limits on the AC transmission lines and other constraints such as interface limits, and other decisions such as the optimal flow on DC lines and flow control angles if they are defined. The VS-OPF uses a linearization of the power flow equations which consider only a real power flows and assumes voltages are all 1 p.u. For the purposes of determining real power flows, the linearized DC-OPF assumes that resistance is small, and voltages are all 1 p.u.

2.1.4 Markets

The defined techno-economic model accounts for several markets which influence the power system performance, such as electrical energy market, emissions market (ETS), fuel market and heat market. Electrical market defined here uses the forecasted prices from year 2020 until year 2043 based on the scenario defined in Section 2.3. This energy market is connected to one 220 kV node. Trades to and from the energy market are made at this node. The megawatt trades act like pseudo loads (for sales) or generators (for purchases). The nodal price[2] reflect the marginal cost of production at the node i.e., the external market prices will not always set the prices at these buses.

To model real life situations, the price signals and incentives are introduced in emission, fuel and heat segment of power system. These markets are also based on the price forecasts from year 2020 until year 2043 based on the modelled scenarios.

2.1.5 Simulations

Techno-economic model in this study refers to a series of linear programs (LPs) e.g. one for each day or week modelled, and within each of these times steps there can be multiple problems each with small differences like the addition of transmission constraints. When an LP has been solved, and then is resolved with modifications it is often possible to start the LP solution algorithm from the last optimal solution. When this is done it is called either a warm start or hot start: a hot start occurs when only minor modifications have been made e.g., changing an objective function value or right-hand side value, whereas a warm start covers all modifications including adding or deleting entire constraints. Warm or hot starts are always performed using the simplex method and hence if the interior point method is run it is always supplemented with simplex so that warm/hot starts can be done [9]. Specifically, in this study the techno-economic model is solved using the CPLEX 12.10.0.0

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[2] Nodal pricing refers to the calculation of electric prices at each node/bus in a power network, whereby the price reflects the marginal cost (to the system) of serving one more unit of load at that bus, or alternatively the price (the system) would be prepared to pay for one more unit of generation at the node.

solver. CPLEX [10] is a mathematical programming solver for linear programming, mixed integer programming, quadratic programming and quadratically constrained programming problems.

The simulations are done using the techno-economic model for time horizon from 2020 till 2050 where all forecasted data in simulation is done in accordance with reference values from the modelled scenarios.

Study considers all the important aspects which define the Croatian power system such as the: imported electricity; long-term projections of electricity load; electricity prices; fuel prices and CO2 emission prices; water availability; intermittence of wind and solar energy; models of generating units and projections of installed power and generation increase in Croatian power mix according to the modelled scenarios. Also, discounting is done in accordance with the input data. Power plant technical details, efficiencies, capacity factors etc. are obtained from owners and/or used directly from the modelled scenarios. Transmission cost and projections of additional investments in transmission system are considered. Also, additional investment needed in energy storage and transmission system to accommodate intermittent RES is accounted for. The carbon capture and storage (CCS) is accounted for and is done in accordance with input data. The planned decommissioning of generating units is done in accordance with input data. Decommission costs are accounted for and are in accordance with NEK owner projection. Decommission costs of NEK are considered in both cases i.e. the case of early retirement in 2023 and retirement in 2043.

2.1.6 Limitations of the modelling approach

Techno-economic model is basically a series of LPs solved using the CPLEX solver which accounts for all technical and economical details of generators, loads, transmission, intermittency of RES. It uses the detailed technical models to provide high quality solutions. However, following limitations and assumptions can be identified.

Generator models are not a dynamic model and cannot analyse the dynamic properties (inertial response, frequency response, voltage and current time change) of the generators.

Transmission model: loads and generation in this model are connected via equivalent high-voltage (HV) transmission grid i.e., it is assumed all generation and loads are connected to HV nodes and nodes are interconnected with HV lines. Transmission is modelled as a Plexos default large-scale HV grid with VS-OPF as a power flow method with a single slack bus. This model is not a model of a dynamic behaviour of the system i.e., it is not a dynamic model and does not provide power system stability analysis. The transmission network is assumed to carry only real power. Load and generation are in terms of real power (MW of electricity).

System dynamics - this model is not a model of a dynamic behaviour of the system i.e., it is not a dynamic model and does not provide power system stability analysis whether it be steady state stability, transient stability or dynamic stability.

Natural conditions - it is assumed that average yearly 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 [3]. Yearly potential for energy production may vary especially for hydro power plants and is usually compensated for with other sources or imports in cases of lower production. In the sensitivity analysis, the results are tested also for modification of some of the input data (not related to natural resources availability).

2.2 Scenarios

To assess the energy, economic and environmental impacts of the NEK dispatch on the Republic of Croatia and the Croatian power system in time horizon from 2020 to 2043, the assumptions found in Energy development strategy of Croatia are followed [3]. Two main cases were analysed: 1st case is operation of NEK until 2043 and 2nd case is operation of NEK until 2023 and then its replacement with the most cost-competitive alternative sources.

These two cases are evaluated for two scenarios (Scenario 1 and Scenario SN) which have high development impact on 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.

2.3 Input data

The main input data origins from the technical basis for development of the Energy Strategy [8] and technical basis for development of Climate-neutral Scenario [6]. Study considers all the important aspects which define the Croatian power system such as the imported electricity, long-term projections of electricity load, electricity prices, fuel prices and CO2 emission prices, water availability, intermittence of wind and solar energy, models of generating units and projections of installed power and generation increase in Croatian power mix according to scenario S1 and SN. Also, discounting is done according to S1 scenario. Power plant technical details, efficiencies, capacity factors etc. are obtained from owners and/or used directly from S1 and SN scenarios. Transmission cost and projections of additional investments in transmission system are considered and are according to S1 and SN. Also, additional investment needed in energy storage and transmission system to accommodate intermittent RES is accounted for. The CCS is accounted for and that is done in accordance with scenario SN since scenario SN is only scenario where it is envisioned to be introduced around year 2040 on gas units which are only conventional powered power plants to be in operation at that time. The planned decommissioning of generating units is done in accordance with S1 and SN scenarios. NEK decommission costs are accounted for and are in accordance with NEK owner's projection. Decommission costs of NEK are considered in both cases i.e. the case of early retirement in 2023 and retirement in 2043, and they are the same. The decommission costs are in both cases expenses for nuclear technology, but in this analysis they are paid by the owners, not by the plant. That means that for the case of early NEK retirement they should be paid from owner's other resources, and in the case of extended operation they will be paid by owner from the difference between NEK electricity production and market price. For additional 20 years of operation collected amount of money is little bit less than 200 MEUR and the same amount of money should come from other owner's sources in case of early NEK retirement.

It should be mentioned that Croatian Energy strategy was based on the data from the document "EU Reference Scenario 2016 Energy, transport and GHG emissions" [11]. The Strategy was approved in 2020, after the new EU Reference Scenario 2020 document was issued. Most important difference between two reference documents is increase in fossil fuel prices and increase in European Union Allowance (EUA) price. Those changes have quantitative influence on the results of this study, but have no influence on its conclusions.

Some of the key input data is shown in this Section, while more detailed data can be found in the Technical basis for development of the Energy Strategy [8] and Technical basis for development of Climate-neutral Scenario [6].

Here, some data were amended by the latest information provided by the NEK. The planned outages of NEK due to the maintenance needs are scheduled after cycles of 18 months with a duration of 30 days. Revenue and expense projections for the period of each scenario have been prepared as fixed prices, based on January 2021, based on the data received from NEK, therefore inflation or other price changes are not taken into account. Expense projection includes all cost categories from the business plan. The projections of prices range from 28-33 EUR/MWh (30.5 in average) early shutdown of the plant and range from 23-31 EUR/MWh (29.0 EUR/MWh in average) for expected lifetime extension until the year 2043. Any other future dues, taxes etc., that are not included in current legislation are not considered in the expense projection (as they are not certain or not known at the time of the analysis). The price of electricity is defined according to the 2001 Agreement and Memorandum of Association principals; the price should cover all costs, which means that there is no profit or loss.

The full scope of capital works relating to the Safety Upgrade Program (SUP) [12] were be performed between 2014 and 2021 and it is not included in analysis because already spent and have no direct influence on assessment of NEK future operation options.

Average hourly wind electricity production in period 2019-2020 was 182.0 MW with maximum of 717.4 MW and minimum of 2.4 MW [13]. Average hourly solar electricity production in period 2019-2020 was 8.3 MW with maximum of 46 MW and minimum of 0 MW [13]. The same scaled solar availability is used in the whole analysis, with average capacity factor of with the capacity factor of 29.9% for wind and 14.9% for solar.

Besides the listed data on planned production and costs of NEK, following key data from technical basis for Energy Strategy and Climate-neutral scenario are used. The costs of fuels, average market electricity prices and costs of CO2 allowances are listed in Table 1. Current EUA price is already larger than assumed one (over 50 EUR/tCO2) and it can be expected that increase of emission allowance price will be faster than assumed. Due to assumed large fraction of RES power plants in used scenarios we are not expecting to see big influence on 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)	63.0	80.0	82.0	84.0
Price of natural gas (USD/GJ)	6.45	8.15	9.1	10.05

Assumed discount rate used was 8%, as in Green Book for Energy Strategy. Further, the costs of technologies are integrated in the model, based on the same source [8].

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

Transmission costs, grid infrastructure and other external costs associated with grid enhancement have been included in the scope of this analysis. Based on the given costs in Scenario S1 and Scenario SN, in case of optimization of new installed capacities for case without NEK after 2023, the additional costs of investments in grid infrastructure per MW of variable renewable energy sources (wind and solar) are included in the optimization which can be translated to about 8 EUR/MWh, which is in range of International Energy Agency (IEA) assessment of 2-10 USD/MWh [14]. Further, total of 400 MW of battery energy systems until 2050 are foreseen in S1 scenario and 1200 MW until 2050 in SN scenario. In the model, linear growth is assumed. Real cost inputs, stated in 2020 prices shall be used for determining the LCOE. The LCOE is stated for 2020.

3 RESULTS AND DISCUSSION

In this Section, a comparative analysis of scenarios is provided, including key investment assessment indicators and power system details for analysed time horizon from 2020 to 2043. That includes: installed capacities, generation, CO_2 emissions, annualized electricity production costs, total costs and system LCOE for analysed time horizon from 2020 to 2043. Techno-economic model is created to evaluate interaction of power system and NEK in case of retirement in year 2023 and extended life operation to year 2043. Also, when NEK is retired, it is investigated which alternative power sources such as wind, solar, biomass, geothermal, gas, coal and hydro, or energy imports can most cost effectively replace NEK having in mind that replacements should be the same in terms of energy. This all is done for the scenario S1 and SN. The CCS is accounted for and that is done in accordance with scenario SN since scenario SN is the only strategy scenario where CCS is envisioned to be used. CCS is assumed to be applied in the year 2040 on gas units which are only conventional powered power plants to be in operation at that time.

The simulations are conducted using forecasted data (electricity prices, fuel prices, load values) based on the S1 scenario. Also, in the simulation, yearly generation volumes of all power plants are matched to those values in scenario S1 and SN respectively. Simulation is conducted for time horizon of 31 years (from 1.1.2020. till 31.12.2050) with an hourly resolution. This is done for four simulation phases: 1st phase: long term plan for expansion planning, 2nd phase: PASA for calculation of system adequacy, 3rd phase: for decomposing the long-term constraints and creating weekly set values; 4th phase: optimal hourly dispatch considering power plant constraints, ramp rates, heat rates and other technical and economical properties.

3.1 Energy and GHG emissions

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

Results point out that the most cost-effective replacement technologies for NEK considering the costs of produced energy, in case of its early retirement in 2023, are wind and photovoltaic power plants. However, this replacement and transition towards a system with higher shares of variable RES requires systematic changes and cannot happen instantly. Therefore, due to the required development time and intermittency of RES, scenarios with the early retirement of NEK initially show substantial increase in imports of electricity and use of natural gas power plants in the system. In the process, additional costs of power system development/operation due to introduction of RES (depending on their fraction) were taken into account in terms of expansion of the grid and storage for balancing services. Planned storage power in the system is from 50 MW in 2023 to 250 MW in 2043 (storage capacity from 65 to 320 MWh) in S1 scenario. That is energy storage needed for successful operation of the system with given RES fractions. It is not used just to secure replacement of NEK production. The replacement of high capacity factor plant is guaranteed for average weather conditions, based on surplus RES plants capacity and their diversity (hydro, wind and PV), participation of other power plants in the system and to some extent use of energy storage.

Simulation results on cost-optimal pathway in S1 scenario show that the early retirement of NEK in 2023 means that the NEK should be replaced by solar power plants with installed capacity of 750 MW whose commission should start in year 2031 (250 MW in 2031, 250 MW in 2032 and 250 MW in 2033). Also, NEK is replaced by wind power plants with installed capacity of 750 MW whose commissions starts around year 2030 (300 MW in 2030, 300 MW in 2031 and 150 MW in year 2032). Simulation results in SN scenario show that the early retirement of NEK in 2023 in SN scenarios means that the NEK should be replaced by solar power plants with the yearly build distribution of 250 MW in 2031, 250 in year 2032 and 250 in year 2033. Also, NEK is replaced by wind power plants whose commissions start around year 2030 with the build schedule of 300 MW in year 2030, 300 MW in year 2031 and 150 MW in year 2032. The date of commissioning is entirely decided by the optimization procedure in 1st phase of Plexos solving procedure is to minimize total system NPV. It is evident that import of electricity is seen as cost-effective solution in initial years. This should be observed considering the fact that additional solar and wind power plants are being built in the observed scenarios anyhow [6] [8]. Also, the Croatia is modelled as price-taker of energy from the external markets, assuming known projected costs. In reality, prices could be somewhat higher without NEK participation in the EU-wide electricity market.

Examining the impact of NEK early retirement in 2023 on overall installed capacity mix in the Croatian power system shows that due to the lower capacity factors of alternative power plants (solar and wind power plants) which replace the NEK in terms of energy (need to produce the same amount of energy as NEK over the entire simulation horizon), they need to have much higher installed capacity (Figure 1). This increase capacity is clearly visible in year 2030 and later when new wind and solar units are introduced. It is important to note that the simulation results of the techno-economic model showed that in case of early NEK retirement in year 2023, the new alternative sun and wind units could be less economically favourable than electricity imports before year 2030. This means that early retirement of NEK in 2023 could have a negative impact on the generation adequacy, system security and stability in period from 2023 to 2030. Further, the economy would be more sensitive to external risks.

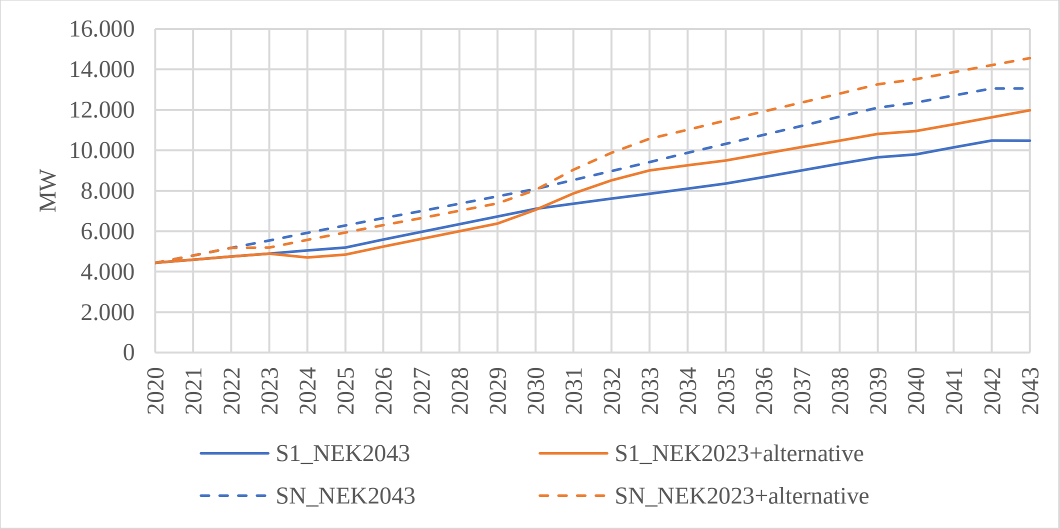

Figure 1: Comparison of the installed capacity in the analysed cases

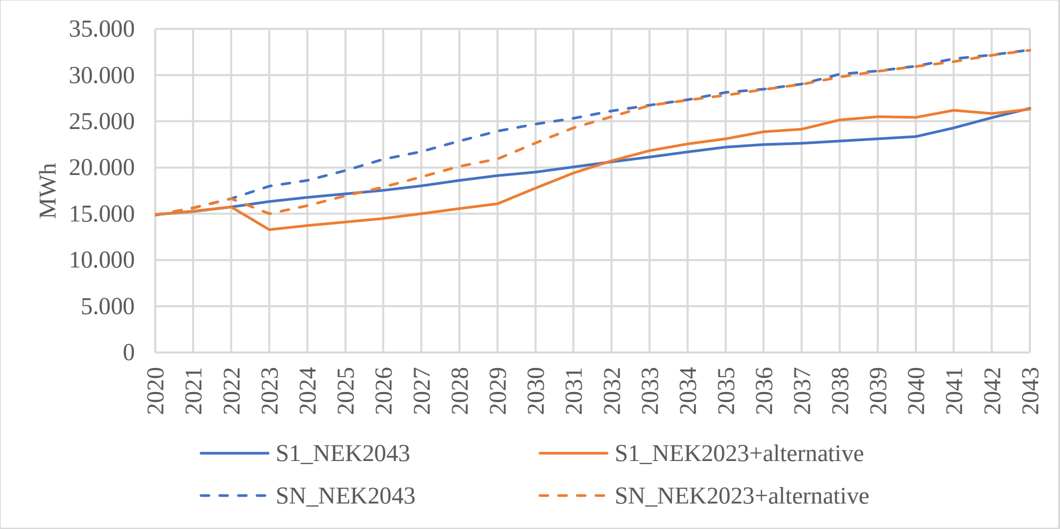

Figure 2: Comparison of the produced electricity in the analysed cases

In Figure 3, time-dependent CO2 emissions are shown for cases with and without NEK lifetime extension. The environmental benefits of prolonged NEK operation can be clearly seen since it means 11,193 ktCO2 less in Croatian environment during the period from 2023 till 2043 in S1 scenario. This is mainly due to less CO2 emission from gas units in case of NEK life extension. When NEK is retired in 2023 and replaced by solar and wind generation this means more gas-powered generation which are peaking units and are used to balance unavailable wind and solar generation in particular hour. In percentage terms, NEK life prolongation means around 21.3 % less CO_2 pollution. It should be said that EUA price used in calculation is taken from the Croatian Energy Strategy. Current EUA price is over 50 EUR/tCO2. That means, in simple terms, we can see additional increase in price due to increased emission in case of NEK early shutdown for up to 300 million EUR. There is no immediate increase in CO2 emission due to time needed to deploy new power plants after NEK closure. In that period import has to be used.

In SN scenario environmental aspect of having NEK in operation till 2043 is beneficial since it means 2,024 ktCO$_2$ less during the period from 2023 till 2043. This is mainly due to less production from gas units in case of NEK life extension. When NEK is retired in 2023 and replaced by solar and wind generation this means more gas-powered generation which are a peaking units and are used to balance unavailable wind and solar generation in particular hour. In percentage terms, NEK life prolongation means around 4.7 % less CO2 pollution in Croatia for strategy Scenario SN. Compared to the Scenario S1, there is a significant drop in CO2 emissions in Scenario SN in second half of the graph due to implementation of CCS technologies from the year 2035 as envisioned in Scenario SN.

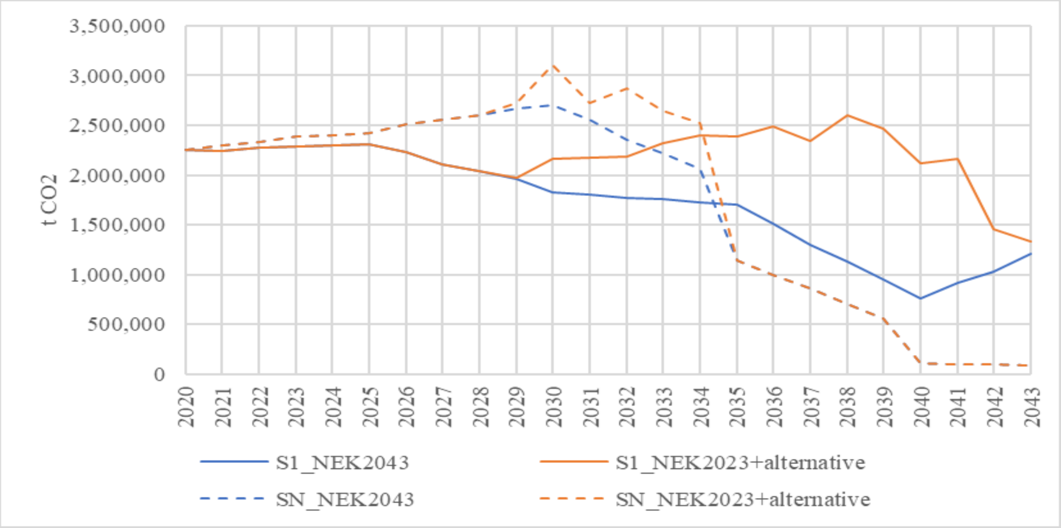

Figure 3: Comparison of CO2 emissions in analyzed cases

Figure 4 shows the total yearly system cost for both scenarios (S1 and SN) and both cases (NEK operation till 2043 and NEK early retirement in 2023). This graph shows that operation of NEK untill 2043 means lower total system cost of Croatian power system beginning from 2023 till the 2043. Compared to early retirement of NEK, the case of NEK operation until 2043 is less expensive solution for Croatia and Croatian power system as a whole since it means 7.4 % lower total system costs in S1 scenario, which in absolute terms is undiscounted saving of 2.15 billion EUR for Croatian power system as a whole. In SN scenario having NEK in operation till the 2043 means 5.9 % lower total system costs which in absolute terms is undiscounted savings of 2.247 billion EUR.

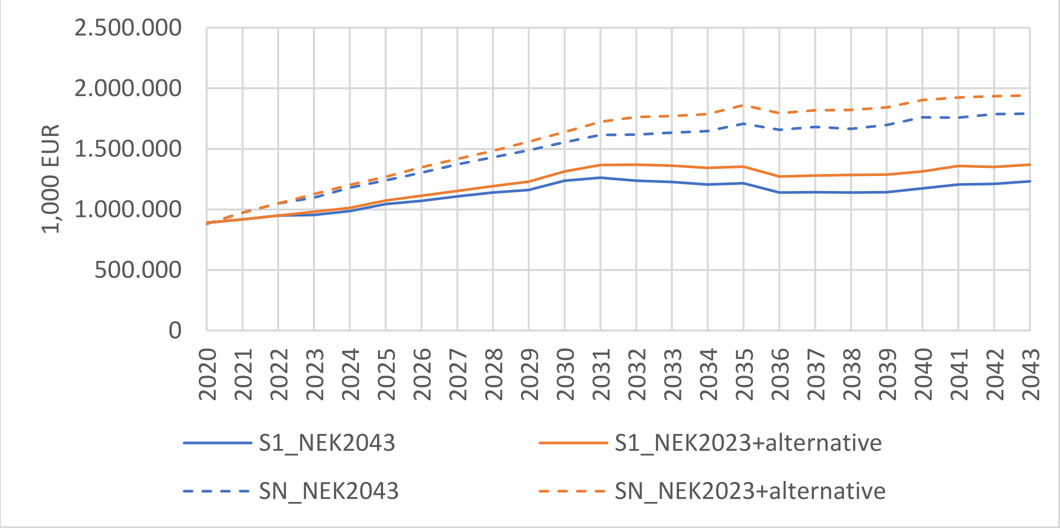

Figure 4: Total yearly system costs

Figure 5 and Table 2 show total yearly system cost of Croatian power system divided by yearly electricity generation i.e., system levelized cost of energy in €/MWh. The average cost of electricity is around 7% lower in case of NEK operation until 2043 compared to early retirement, in S1 scenario. This cost reduction caused by NEK operation till 2043 will undoubtedly mean less expensive electricity on Croatian wholesale electricity market and cheaper electricity for Croatian consumers. Similar trend is seen also in SN scenario.

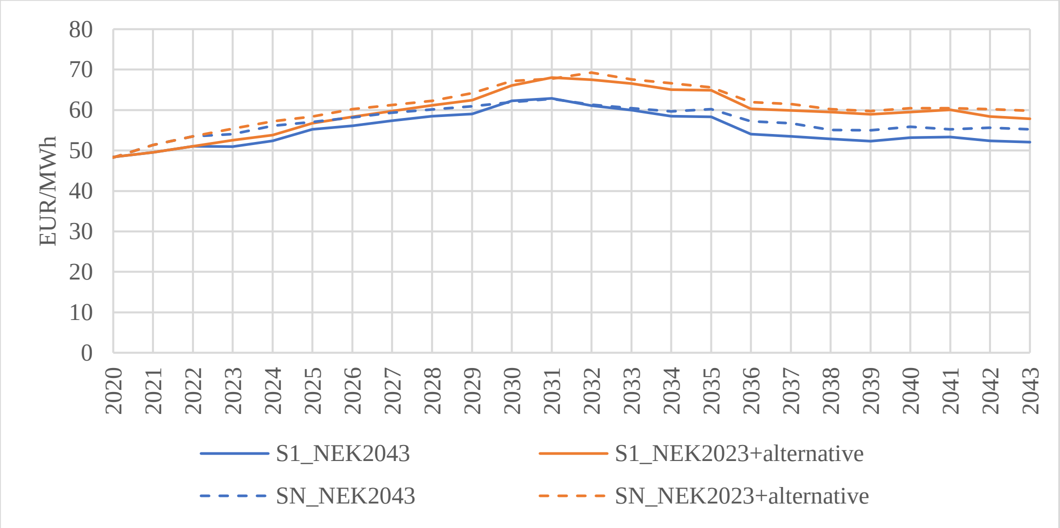

Figure 5: Comparison of Annualized electricity production costs in analyzed cases

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

The summary results on system levelized cost of electricity are shown in Table 3 and Figure 6. Further summary on total costs and CO_2 emissions are shown in Table 3. Main findings can be summarized as follows:

- In S1 scenario, it is evident that extending operation of NEK until 2043 leads to decrease of system LCOE by 3.14 EUR/MWh or 5.4 % and decrease of total system costs by 2.149 bln. EUR (7.4 %) compared to case without NEK life extension. Therefore, the life extension of NEK proves to be economically more favorable. Besides the economic aspects, the NEK life extension is more favorable from environmental perspective since NEK life extension means 21.3 % less CO2 emissions compared to case of NEK early retirement.

- These conclusions can be repeated for SN scenario, where extending operation of NEK until 2043 leads to decrease of system LCOE by 3.05 EUR/MWh or 5.1 % and decrease of total system costs by 2.247 bln. EUR (5.9 %) compared to cases without NEK life extension. So, the life extension of NEK proves to be economically more favorable also in the SN scenario. Moreover, the NEK life extension leads to lower CO_2 emissions also in this scenario, but for lower amount (4.7 %) due to the fact of high ambition and increased installations of renewable energy sources and batteries as well as CCS technology for natural gas plants in this scenario already decreased CO_2 emission, leaving less space for slight increase in case of earlier retirement of NEK (which is non-CO_2 electricity 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 %)***

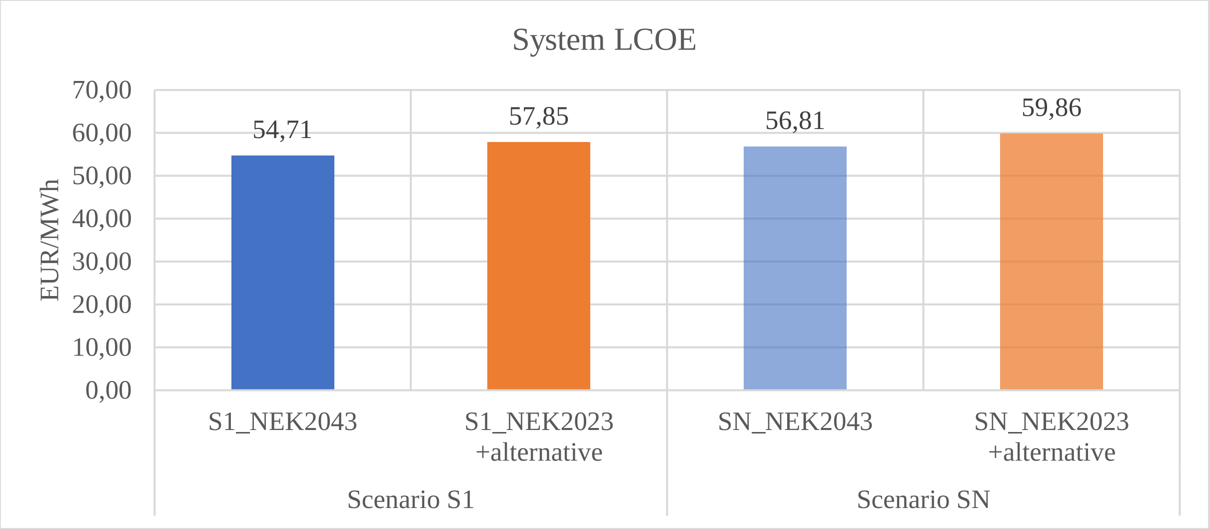

Figure 6: Comparison of system LCOE in the analyzed scenarios and cases

3.2 Sensitivity analysis

For scenario S1 the effects of different discount rates and electricity prices on system LCOE are shown in Figure 7. It can be observed that changes of import prices have relatively smaller impacts in S1 scenario, especially with NEK operation until 2043, as it is a scenario that represents outputs as in Energy strategy, where net imports decrease. Impacts of different discount rates are more significant, as those directly affect feasibilities of new investments and changes in total costs and levelized systems costs that appear over observed time horizon.

In the sensitivity analysis of impacts of 5% higher market prices in the case with NEK early retirement in 2023, increased market prices lead to increased system levelized costs until 2033. In period 2034-2043, due to investments in new capacity and increased exports, system levelized cost are lower than in the base case. Those opposing effects lead to slight decrease in system LCOE over the observed time horizon 2020-2043.

In the sensitivity analysis of a lower discount rate of 2%, there is a substantial decrease in system levelized cost in period 2020-2043 for both cases - with NEK operation until 2043 and for a case with shorter NEK operation until 2023. This is due the fact that lower discount rates lead to lower annualized investment costs and more competitive domestic electricity production. That led to decrease in system LCOE from 54.7 EUR/kWh to 49.9 EUR/kWh (by 8.8%) in case with extended NEK operation, and from 57.8 to 52.3 EUR/kWh (by 9.5%) for the case with earlier NEK retirement.

On the other hand, increasing the discount rate to 10% from base rate of 8% has opposite effect on system levelized costs and there is an increase in yearly system levelized costs. This is because increased discount rate discourages investing in RES and domestic electricity production (since assumption is that electricity prices stayed at the relatively low prices which are same as in base case). That led to increase in system LCOE from 54.7 EUR/kWh to 56.9 EUR/kWh (by 4.0%) in case with extended NEK operation, and from 57.8 to 58.6 EUR/kWh (by 1.4%) for the case with earlier NEK retirement.

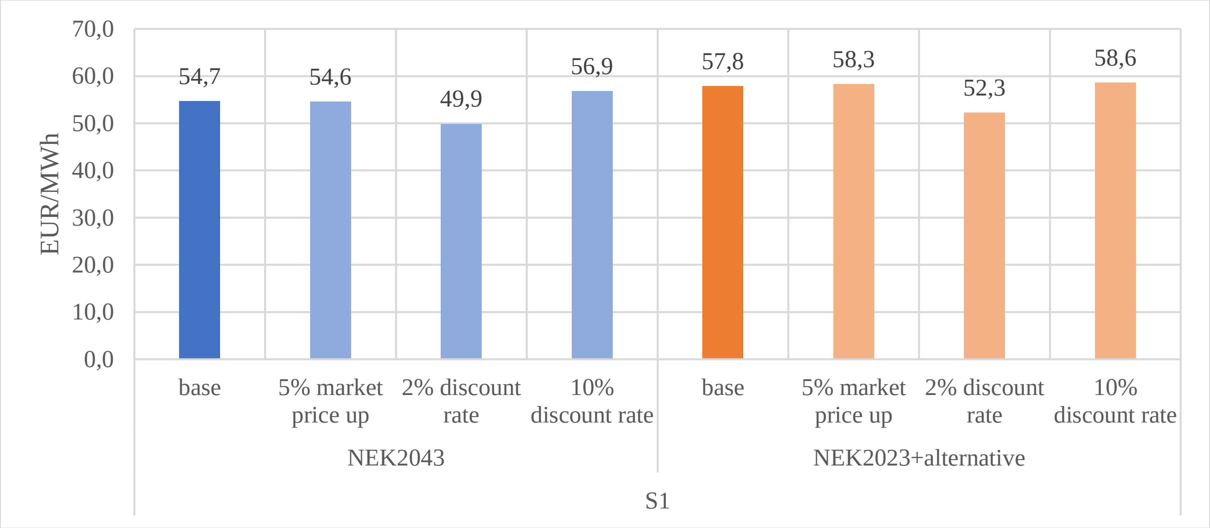

Figure 7: System LCOE for the S1 scenario and sensitivity analysis in the period 2020 – 2043

The results of sensitivity analysis for the SN scenario and impacts on the system LCOE over the observed time horizon are shown in Figure 8. It can be observed that increase of import prices by 5% have relatively lower impacts than changes of discount rates from 8% to 2% and 10%.

In the sensitivity analysis of impacts of 5% higher market prices in the case with NEK early retirement in 2023, increased market prices lead to increased system levelized costs until 2030. In period 2031-2034 due to more competitive domestic production and decreased imports, yearly system levelized cost are lower than in the base case. Those effects led to slight decrease in system LCOE over the observed time horizon 2020-2043 in both cases.

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

On the other hand, increasing the discount rate to 10% from base rate of 8% has opposite effect on system levelized costs and there is an increase in yearly system levelized costs. The exception is in the case with NEK early retirement and in the period 2030-2033, when there is dip in yearly system levelized costs compared to base case, due to postponed investments in new capacity. However, this postponement reflects in increased costs afterwards. The increased discount rate discourages investing in RES as potential new domestic electricity production becomes more costly (since assumption is that market electricity prices stayed at the relatively low prices which are same as in base case). In total, that resulted in an increase in system LCOE from 56.8 EUR/kWh to 58.8 EUR/kWh (by 3.5%) in case with extended NEK operation, and from 59.9 to 60.2 EUR/kWh (by 0.5%) for the case with earlier NEK retirement.

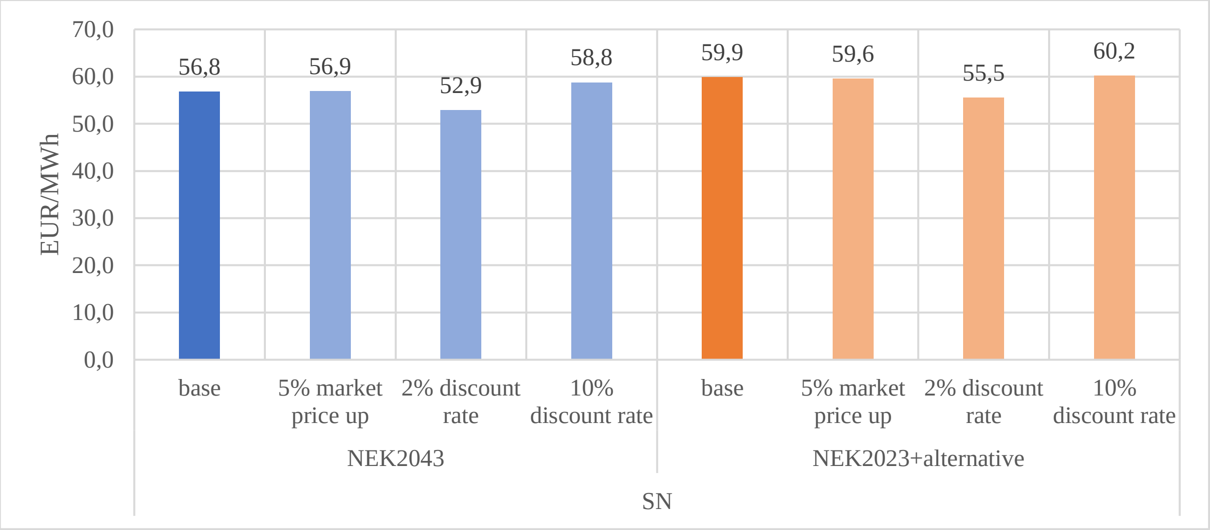

Figure 8: System LCOE for the SN scenario and sensitivity analysis in the period 2020 – 2043

4 CONCLUSION

NPP Krško is, after almost 40 years of successful operation, facing the end of its originally assumed design life. Thanks to a proper maintenance, planning and investment, including replacement and upgrades of old equipment, and upgrades of safety systems, NPP Krško is ready for life extension of additional 20 years. The development plans of both Croatia and Slovenia were based on the assumption of life time extension of the plant. It has recently been acknowledged that an environmental impact assessment is necessary to address plant’s lifetime extension. This study was prepared to compare techno-economic and ecological aspects of extended NEK operation and its shutdown and replacement of its production with most cost-effective power sources (RES in this case).

This study is based on the data and assumptions from Croatian Energy strategy approved in 2020. In meantime some important inputs were changed. That is mostly related to increase in fossil fuel, commodities and electricity prices and increase in EUA price. Those changes have quantitative influence (e.g. use of current EUA price can increase expense of NEK replacement in Case of S1 for 300 million EUR) on the results of this study, in a sense that extended NEK operation is even more favorable, but have no influence on its conclusions.

As evident from the all analysed scenarios, cases and conducted sensitivity analysis, the life extension of NEK proves to be more favorable option in terms of economic indicators and greenhouse gas emissions.

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