

Power Flows and System Dynamics Influence of NPP Krško Lifetime Extension on Croatian Power System

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ABSTRACT

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. When addressing environmental impacts of any existing energy source it is important to see what are the alternative ways to produce the same amount of energy and what are consequences of operation of both original and potential replacement power sources. In that regard this paper describes the assessment that was performed to explore the influence of NPP Krško on power systems of Slovenia and Croatia in the period between 2023 and 2043. Multi-scenario analysis was performed for assumed development stages of the two power systems mainly to assess the importance of NPP Krško in comparison to potentially newly added production, mainly wind and solar. The results are shown from twofold perspectives 1) power flows perspective observing the losses, loadings, voltage conditions and 2) power system dynamics perspective observing the stability of the system.

Keywords: *power flows analysis, power system dynamics, lifetime extension*

1 INTRODUCTION

The Croatian and Slovenian power systems have long relied on NPP Krško as a stable baseload source. With the plant approaching the end of its original 40-year design life, a decision on lifetime extension has become one of the key energy policy questions in both countries. The development plans of both Croatia and Slovenia have assumed continued operation of the plant. Unlike EIAs for new facilities, such an assessment should focus specifically on the impacts of continued operation. When addressing environmental impacts of any existing energy source it is important to see what are the alternative ways to produce the same amount of energy and what are the consequences of operating both the original and potential replacement power sources.

In that regard this paper describes the assessment that was performed to explore the influence of NPP Krško on power systems of Slovenia and Croatia in the period between 2023 and 2043. Multi-scenario analysis was performed for assumed development stages of the two power systems mainly to assess the importance of NPP Krško in comparison to potentially newly added production, mainly wind and solar. The results are shown from twofold perspectives:

- 1) power flows perspective observing the losses, loadings, voltage conditions and
- 2) power system dynamics perspective observing the stability of the system.

Two scenarios from Croatian energy strategy were used in analyses to describe future development of electric power production in Croatia, S1 and SN. Both scenarios are based mostly on introduction of RES power plants and SN is mentioned to be CO₂ neutral (additional reduction

of CO₂ emission compared to S1). For each scenario two cases were calculated. First case (*case a*) assumes, more likely situation, life extension of NPP Krško and its operation in mentioned period. The second case (*case b*) assumes NPP Krško shutting down and introduction of replacement power sources able to produce the same amount of energy.

The main focus of this study is the assessment of NPP Krško's influence to power flows and system dynamics in the Croatian power system. It will address:

- Power flows and steady state analysis of losses and voltages using a detailed power grid model that assumes certain direction of Croatian power system development primarily in the regard to the integration of large share of renewable energy sources (RES);
- Qualitative impact on grid frequency dynamics studied on the simplified model of isolated Croatian power system with the aim to assess the impact of NPP Krško operation on Croatian power system.

All conducted analysis are in accordance with the most recent 10 years 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-E (European Network of Transmission System Operators) 10-year development plan (TYDP):

- 10 years development plan of the Croatian TSO for the period from 2021-2030 [1],
- 10 years development plans of ENTSO-E (TYDP) [2], [3], [4].

2 POWER FLOW ANALYSIS

2.1 Power system model and assumptions

To conduct power flow analysis the model of the transmission level network is needed as the first prerequisite. The main requirement for this step was the development of the representative model of the current state of the Croatian network starting from the year 2021 and a simplified representation of the wider ENTSO-E network. 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 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.

Regarding the connection level of the NPP Krško which is connected to high voltage (HV) grid (400 kV) the focus of observation was the high voltage Croatian segment of 400 kV and 220 kV networks.

To allow the transmission of power through the main 400 kV and 220 kV voltage lines additional voltage support is required on top of that provided by the production units synchronized to the system.

According to the latest approved 10-year development plans of the Croatian TSO (HOPS), the FACTS devices to regulate the voltage in the high voltage grid are considered in the used PSS/E grid model as well as the devices that are part of the planning process under the SINCROGRID project:

- TS Konjsko – SVC (Static Var Compensator) rated power 250 MVar on 220 kV;
- TS Melina – VSR (Variable Shunt Reactor) rated power 200 MVar on 220 kV;
- TS Mraclin – VSR rated power 100 MVar on 220 kV.
- TS Divača (Slovenia) 400 kV – MSCDN (Mechanically Switched Capacitor with Damping Network) 100 MVar capacitive and VSR 150 MVar inductive.
- TS Beričevo (Slovenia) 400 kV – STATCOM (Static synchronous compensator) 150 MVar inductive / 150 MVar capacitive at 400 kV,

- TS Cirkovce (Slovenia) 400 kV – VSR 150 MVA_r inductive.

FACTS devices deal with the problem of overly high voltages in the Croatian power system in the scenarios of low consumption and high production (of both hydro and wind). FACTS devices affect the 220 kV voltage level and limit it locally to 110% (242 kV). This is specially expressed in the scenarios representing the predicted development status in the next 10 years during the lower consumption periods.

The voltage levels in the developed model are also regulated with the generators connected to the grid. In the Croatian system, the generators are operating in the PV mode (controlling active power and terminal voltage) and are set to maintain voltage level between 1.05 p.u. and 1.1 p.u. depending on their position in the grid and their voltage level. The generators are allowed to change the reactive power output in the range of $\cos \varphi = \pm 0.95$. In the rest of Continental Europe, the generators are operating in either PV or PQ mode based on the analysis of specific historical operational snapshot of the European power system.

The complete list of currently operational power production units in the Croatian power system can be found in [1]. Briefly, the Croatian EPS in its current state consists of close to 5000 MW of installed generation capacity divided approximately as follows: 2100 MW in hydroelectric power plants, 2000 MW in thermal power plants and 850 MW in wind power plants in operation with another 150 MW currently being in test operation which will soon sum up to a capacity of wind of over 1000 MW online. Additionally, the Croatian TSO and other responsible institutions have issued all the allowances for another 300 MW of wind power which are expected to commence the construction in the next 3-year period. All these units are considered in the model with the exact location and grid connection layout.

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.

2.2 Planned new production and transmission capacity

The specifics of the Croatian power system are high density of future wind, solar and hydro power located in an area of not more than 100x100 km which is situated in between Zadar and Split regions. The total amount of installed capacity in that region is predicted to peak at 80% of total Croatian installed capacity in the next 10-year period.

Based on the total number of new production units that are currently in the process of connection consideration (over 110 projects considered with total capacity of approximately 10000 MW as of June 2021, [5]) Croatian power system is facing a significant potential change in its power mix with the inclusion of this considerable number of renewables. The total projects capacity of both transmission level, as mentioned reaching 10000 MW, and distribution level, reaching 1700 MW, is constraining the transmission system and will be a major generator of new investments.

The installed capacity of all the projects approximately corresponds to the installed capacity according to the S1 strategic development plan. Assumed development of wind, solar and hydro total installed capacities according to the strategic plans are mapped to the actual planned production units. The total planned capacities of the projects listed in this section is higher than the capacities according to the strategic plans with and without NPP Krško. Therefore, the capacities of each unit are uniformly scaled such that the total installed capacity in the model and its power production in simulated study-cases is equal to the one estimated by the strategic plans.

The majority of current and future projects aim to connect to 110 kV voltage level, but the bigger share of future power is expected to be connected to 400 kV voltage level (Figure 1). The number of projects and their approximate construction dynamics is shown in Figure 2.

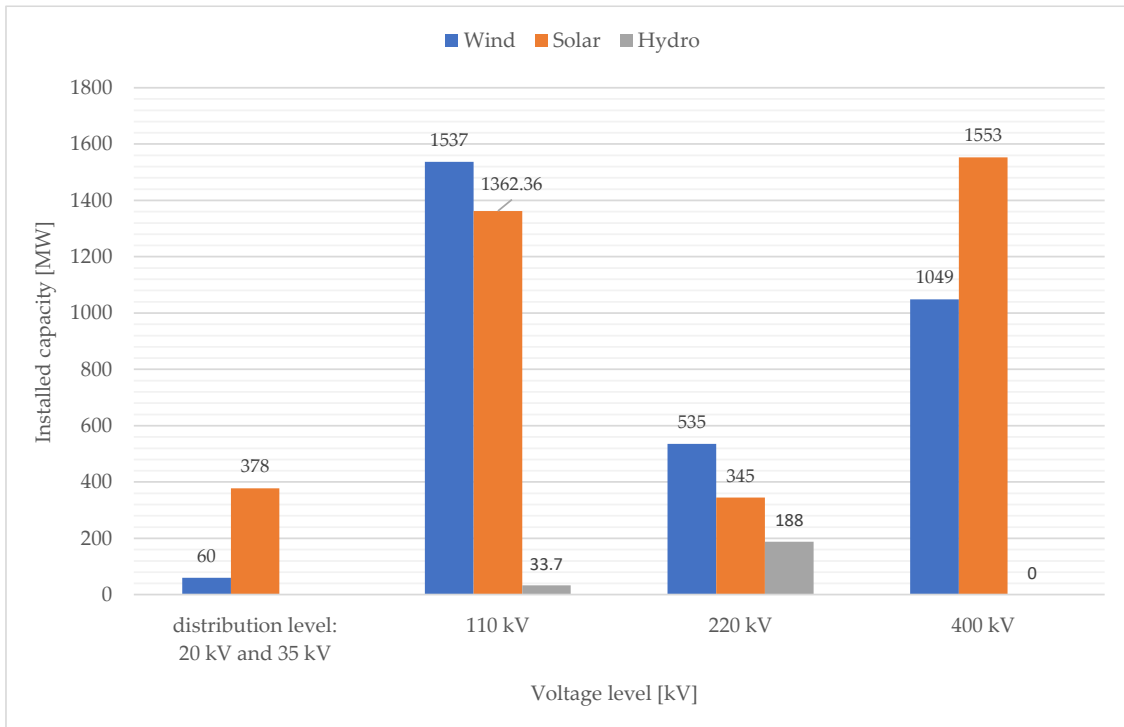


Figure 1 Total planned RES capacity in the period 2020–2043 sorted by voltage levels.

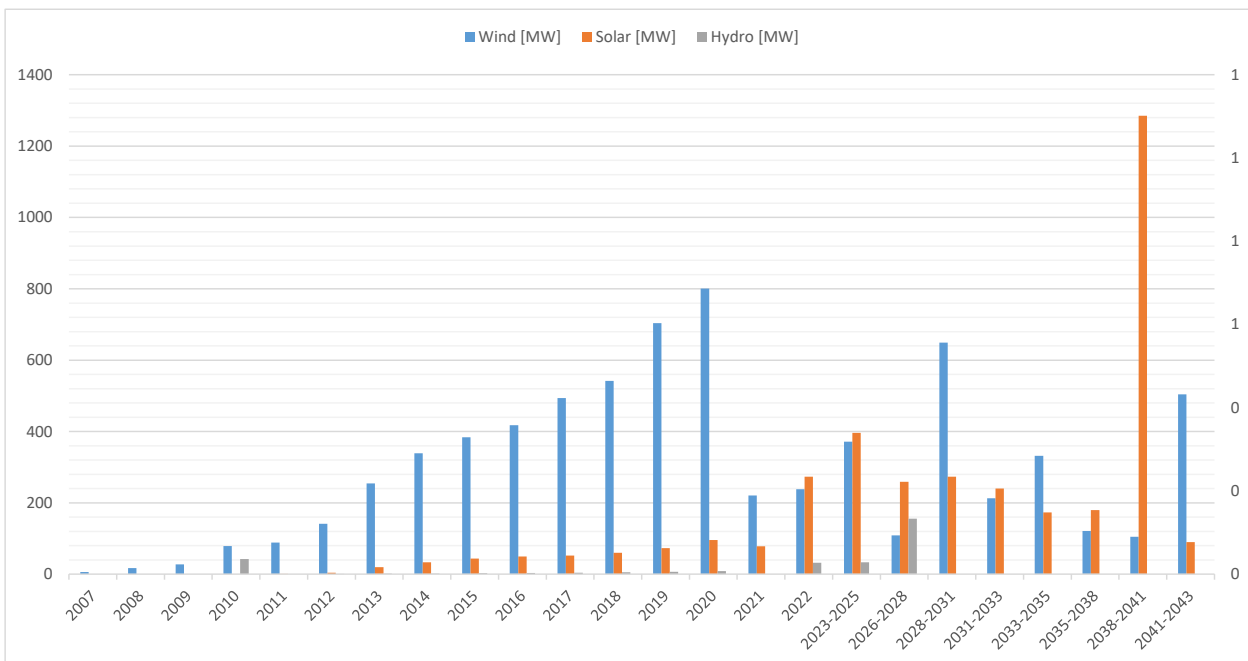


Figure 2 Total planned RES capacity in the period 2020–2043 spread through the expected commissioning years

2.3 Power flow scenarios

As was mentioned before, the developed power flow scenarios using described PSS/E power grid model, with and without NPP Krško, are based on:

1. Scenario 1 (S1) - scenario of accelerated energy transition from Energy development strategy of the Republic of Croatia by 2030 with a view to year 2050

2. Scenario SN (SN) - a climate neutral scenario from report Climate neutral scenario of the Republic of Croatia.

The chosen scenarios can be representative for approximate energy mixes predicted by the strategic documents. Special attention was given to the Development strategy scenario S1 while the scenario SN was briefly compared to S1 since the conclusions and trends do not change.

All the scenarios are satisfactory for the normal operation conditions (N state). In normal operation there are no new problems due to the connection of additional capacity and predicted grid investments.

2.3.1 Development scenario S1

The case-studies representing the development strategy S1 are based on the production mix and total peak powers in different years from 2023 to 2043.

It must be noted that the study-cases represent the power flows in different network time snapshots that deal with the power balance and momentarily power flows while the total energy produced would correspond to the total installed capacity of the technology multiplied by its annual average loading factor. Since average loading factors and exact production of all the units are not publicly available data, we applied the loading factors issued by the system operator HOPS and used by them in the connection procedure analysis (they are publicly available). These factors originate from the separate analysis of coincidence factors and actual production in each hour for the period 2018-2019. Specifically, the high load and mid-to-high production cases, which were chosen as representative for this analysis, come from that analysis.

Additionally, the NPP Krško power of approximately 350 MW was substituted with assumed new production units on their exact locations. This means that their discrete total installed capacity was added to the sum of total installed capacity in Croatia, while this installed capacity was modified with the production factors in accordance with the simulated study-cases to obtain the maximum peak power.

The total load and production were aimed to simulate the high demand and medium to high production of renewables. This is an expected case in the future power system of Croatia which will be characterized with high penetration of renewables exceeding the total demand significantly.

The NPP Krško power can be substituted with a number of production units, primarily wind and solar, based in the coastal region of Croatia and connected to various voltage levels.

The “alternative” production was realized through a selection of realistic projects with exact grid connection location and exact grid connection variant. Therefore, the total production energy mix is not exactly matched to the one used in the Strategy but is closely approximated. The impact of these inconsistencies is not significant, and all the conclusions are not sensitive to that approximation.

The results of snapshot calculations show that it is expected for the Croatian power system to become an exporter of energy in mid to high RES production cases, which are probable to occur in significant number of hours in a year. Installed capacity of wind, solar and hydro in years 2033 and 2043 is 2-3 times greater than the expected peak load. Also, the results show that the cases that include NPP Krško have lower average system loading. That is because NPP Krško is located close to the consumption centers and connected using 400 kV lines, and when its production is substituted with RES plants the lines transferring that power from the southern parts of the Croatian grid towards northern parts are more loaded.

Additionally, the conclusion is that the voltage levels are satisfactory for the considered N state. The impact NPP Krško has on network voltages is not significant with them being slightly higher in the segment of the grid around NPP Krško.

The simplified graphical representations of the most important power flows for the year 2033 for both “a” and “b” cases, are given in Figure 3.

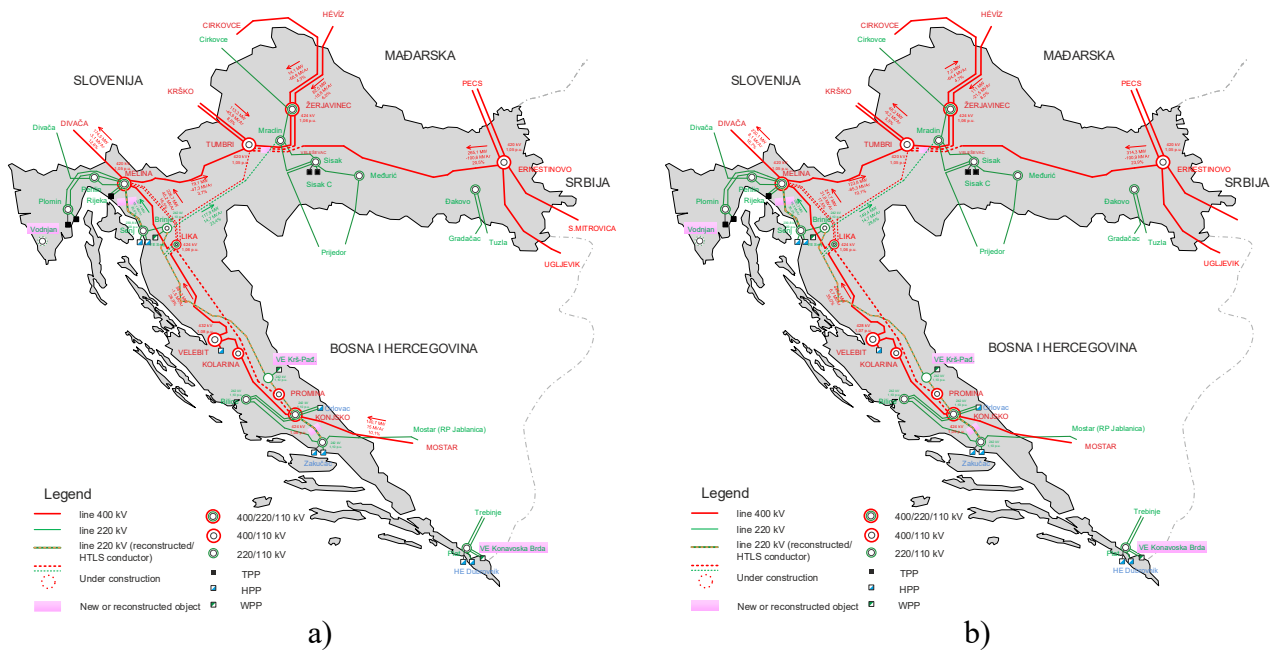


Figure 3 Representative power flows, a) for case-study with NPP Krško in operation, in 2033 – “a_2033”, and b) for case-study with NPP Krško substituted by alternative sources, in 2033 – “b_2033”

2.3.2 Development scenario SN

The scenario is based on CO₂ neutral production mix. The situation in case of SN scenario is very similar to the one in scenario S1. Due to additional RES power sources and need to replace energy produced by classical power plants the installed power is additionally increased. The anticipated installed capacity is 13.8 GW with the peak power around 5.8 GW for 2043. Most of the installed capacity is assumed to be wind 3.5 GW, hydro 3.3 GW and solar 5.8 GW.

The detailed results are not shown for the SN scenario since the conclusions stay like the ones found for scenario S1 with the exception that the grid development process needs to be faster. The grid that is anticipated in SN scenario for year 2043 needs to be mostly built by 2033-2035. The methodology and the modelling are unchanged and similar to S1 development scenario.

2.4 Power flow results

Following the methodology and assumptions above, the analysis was conducted for a selected mid-to-high production grid operation with high demand. These grid operation conditions were selected since it is expected that they will represent the constraining conditions in regard to large system exports. Also, to accommodate the energy consumption segment of the analysis, high demand case was combined with the mid-to-high production in a selected study-cases which are expected to happen in mid-day and late-afternoon segments of each day with significant sun production. The study-cases simulated the grid and addition of new production for a period from 2020 baseline study-case through years 2023, 2033, 2043 study-cases. 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 favorable location of NPP Krško close to consumption centers in the northern parts of Croatia. That part of the country is not expected to experience large penetration of wind and solar RES.

Table 1 shows quantitatively the increase in both the system losses power and average loading of high voltage lines for the case when NPP Krško is replaced with RES sources from scenario S1

compared to the case when NPP Krško is in operation. The values for SN scenario are only slightly different and are not shown explicitly.

Table 1 Comparison between average loadings and system losses for NPP Krško in operation („a“ study-cases) and study-cases with production from alternative sources („b“ study-cases) – S1 scenario

	0_2020 baseline	a_2023	b_2023	a_2033	b_2033	a_2043	b_2043
Average HV lines loading [%]	21,7	20,9	23,4	40,3	43,3	42,4	44,3
Difference*	0,0	+2,5% (increase)		+3,1% (increase)		+1,9% (increase)	
System losses [MW]	89,0	82,6	101,7	220,2	248,0	250,3	284,4
Difference*	0.0	+19,1 MW (increase)		+27,8 MW (increase)		+34,1 MW (increase)	

*case “b” compared (b-a) to case “a” for simulated years

3 SYSTEM DYNAMICS ANALYSIS

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. Nevertheless, the share of non-synchronously connected renewable energy sources is increasing 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 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.

Only synchronously connected power plants contribute to the system inertia since the kinetic energy of non-synchronously connected power plants is “hidden” by the power electronic converters. Note that this only applies to generators with rotating parts such as wind turbines. On the other hand, photovoltaic power plants do not have any rotating parts therefore they have no inherent inertia. Converter-interfaced sources, however, can provide a service called emulated, synthetic or virtual inertia which will be described in more detail in later sections.

Grid inertia is important because it impacts the rate-of-change-of-frequency (RoCoF) and frequency nadir (minimum value of frequency reached during the transient period), alongside the system regulating energy. To assess the impact of NPP Krško on frequency dynamics of Croatian electric power system in island mode, a two-machine system is modelled in MATLAB-Simulink. One machine aggregates all the power plants in the north region including NPP Krško, while the other machine aggregates all the power plants in the south region. The two areas are connected via a 400 kV double line emulating the 400 kV connection between substations Konjsko and Melina. Electric diagram of this two-machine system is shown in Figure 4.

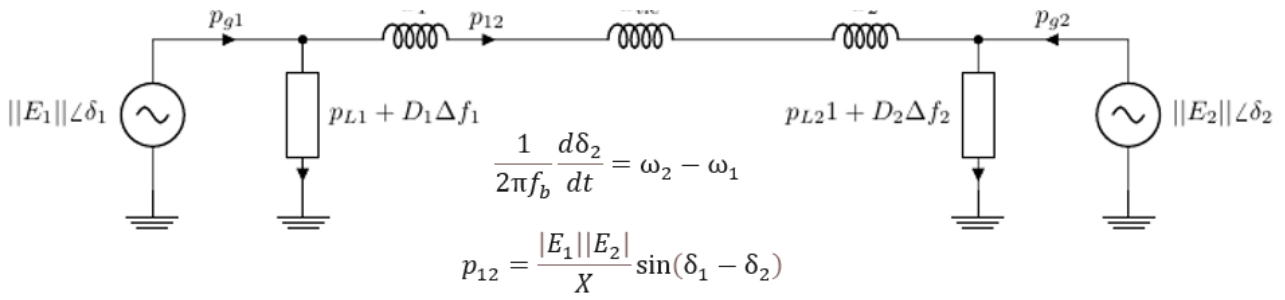


Figure 4 Two-machine system model with mathematical description of the model

A 500 MW generator outage is taken as the load-generation mismatch disturbance, approximately equal to the size of the largest power plant unit in Croatia. Figure 5 shows the frequency dynamics and it can be observed that decommissioning of the NPP Krško causes a lower frequency nadir (bigger maximum frequency deviation).

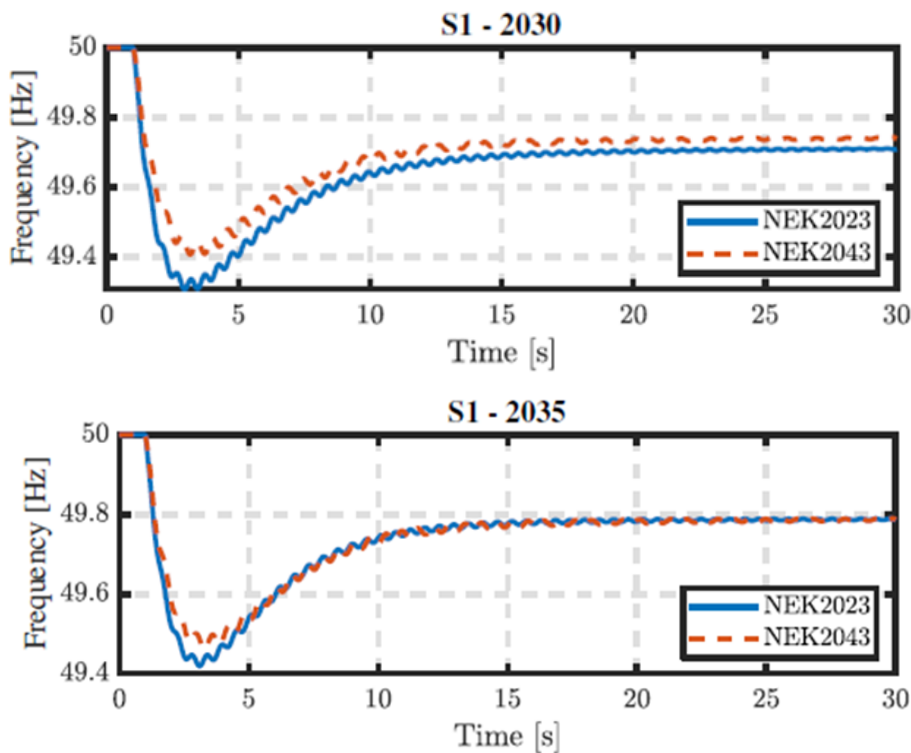


Figure 5 Frequency dynamics after a 500 MW disturbance for grid models with (NEK2043) and without NPP Krško (NEK2023)

Both nadir and RoCoF are shown for the period 2020 – 2050 in 5-year increments in Figure 6. There is no difference between scenarios where NPP Krško is decommissioned in 2023 as opposed to year 2043 for the years 2020, 2045, and 2050 because in the first one, NPP Krško is online in both scenarios and offline for the last two periods.

Although the Croatian power system is well interconnected with the rest of the continental Europe and the rest of the ENTSO-E system and the contribution of NPP Krško is relatively small in that regard, its synchronous rotational energy undoubtedly improves the local dynamic response and inertia of the Croatian power system.

That can be especially important for fast and large disturbances. NPP Krško accounts for more than 20% of synchronous kinetic energy and presents a strong node in the surrounding power system in Croatia that would facilitate transition towards more renewable energy sources in the system.

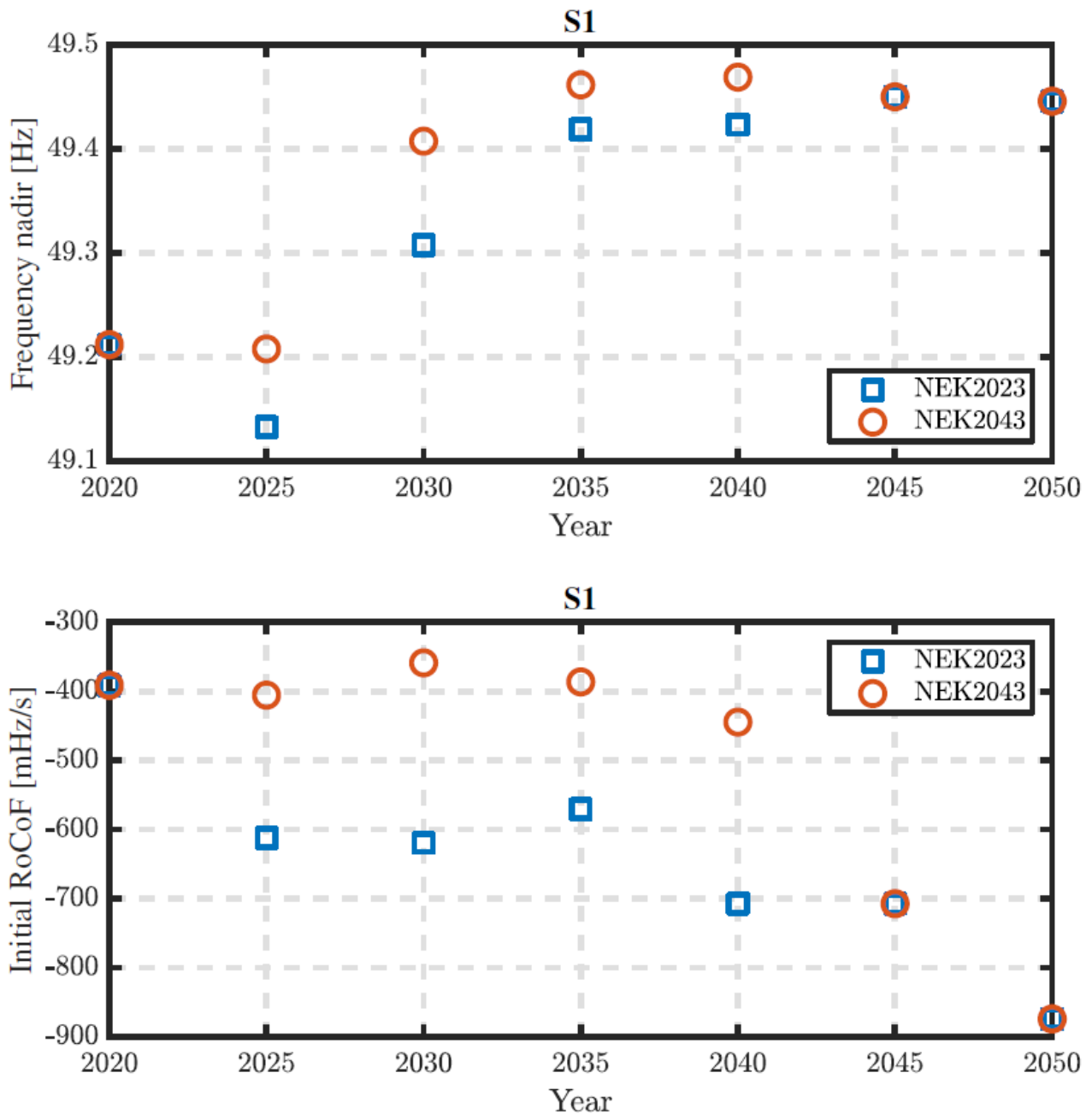


Figure 6 Frequency nadir and initial RoCoF after a 500 MW disturbance with NPP Krško in operation until 2023 (NEK 2023) and in operation until 2043 (NEK2043)

4 CONCLUSION

Taking into account installed capacity of Croatian power system, its interconnections to neighboring power systems and share of the Croatian part of NPP Krško production, overall influence of NPP Krško operation should be limited. Still, due to 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 and considering configuration of the grid, a 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 favorable conditions for RES energy production). 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. All analyses were performed for average meteorological situation and for normal availability of fossil fuels and elements of power system. Rather optimistic rate of RES and grid development, based on Croatian energy strategy, is assumed in this analysis. There is no doubt that assumed RES potential exists, but realization of the plans from the Strategy will depend on many other factors and are associated with some uncertainties. 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.

The impact of NPP Krško operation in the period from year 2023 to year 2043 can be in short summed as follows:

- a) for steady state power flows:
 1. NPP Krško reduces the total network losses,
 2. NPP Krško reduces the average loading of vital 400 kV transmission lines,
 3. NPP Krško has minor influence on steady state voltage conditions in normal operation,

- b) for power system dynamics:
 1. NPP Krško in operation improves the frequency nadir and initial RoCoF,
 2. NPP Krško improves the dynamic response to disturbances.

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