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Model-Based Comparison of Nuclear and Renewable Energy Based Strategies for Slovenia

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Summary **—Decarbonising the primary energy sector is essential for achieving a sustainable electricity supply and requires a transition away from fossil fuels. Coal- and gas-fired plants are expected to remain only as strategic reserves, operating during emergencies or other critical situations. Two development strategies defined in Slovenia's National Energy and Climate Plan are evaluated: a nuclear-based pathway and a renewable-only pathway. A zero-dimensional energy system model with hourly resolution was applied, integrating nuclear, thermal, hydro, wind, solar, and pumped hydro storage to represent projected 2040 conditions. System performance was assessed through grid stability, carbon intensity, import dependency, and spatial efficiency. The nuclear pathway provided stable baseload generation, minimised fluctuations, and reduced reliance on storage and imports. It achieved 113 $kgCO_2eq/MWh$ with land use of 2.4 km^2/TWh. The renewable-only pathway showed high variability, surpluses exceeding several gigawatts, and greater balancing needs, resulting in 148 $kgCO_2eq/MWh$ and land use of 9.1 km^2/TWh. An additional, nuclear-only variant further demonstrated that one reactor can replace several gigawatts of solar capacity while maintaining stability and reducing emissions. The results question the relevance and feasibility of renewable-only strategies and confirm the crucial role of nuclear power in ensuring secure, low-carbon electricity supply.**

Keywords **— energy transition, energy system modelling, energy flows, environmental impact analysis**

I. Introduction

Energy system modeling is essential for evaluating energy supply strategies. Hourly-resolution models capture short-term fluctuations in supply and demand, offering insights into grid reliability and energy security—factors not fully addressed by integral energy balances. Such modeling is particularly important for systems dominated by renewable energy sources (RES), where variability challenges system stability and requires flexible solutions, such as storage or dispatchable load.

A zero-dimensional energy system model was developed to compare nuclear and renewable-based strategies. The model simulates hourly energy flows, integrating nuclear, thermal, solar, wind, and hydropower sources, along with pumped-hydro storage, under the current Slovenian power system and National Energy and Climate Plan (NEPN) [1] projections.

System performance was assessed based on grid stability, greenhouse gas emissions, import dependency, and spatial efficiency. The analysis provides an objective comparison of nuclear and renewable strategies, highlighting their respective roles in a stable, sustainable, and economically -feasible electricity supply.

II. Model Description

The power supply system consists of three primary entities: consumers, producers, and prosumers. Consumers represent the system's load, encompassing industrial facilities, households, and electric vehicle charging stations. Producers serve as energy sources, including various types of power plants. Prosumers, a hybrid category, can function as either consumers or producers depending on system conditions. This category includes energy storage units and cross-border energy flows [2].

Electric power transmission in the system follows the fundamental principle that energy can only flow when there is a difference in thermodynamic potential between producers and consumers. Thus, the system operates by balancing energy flows rather than supplying consumers independently [2]. This results in the core governing equation of the model:

$$\sum_i P_i(t) + \sum_i \dot{E}_i(t) = 0; \forall t \in [[0,\ 8760\,\mathrm{h}]], \quad (1)$$

where P represents the electrical power supplied by producers, and $\dot{E}$ accounts for energy flows related to consumption and prosumption, having positive or negative sign for energy production and consumption respectively. Index i presents individual energy entities. The basic operation of the modeled system is graphically depicted in Fig. 1.

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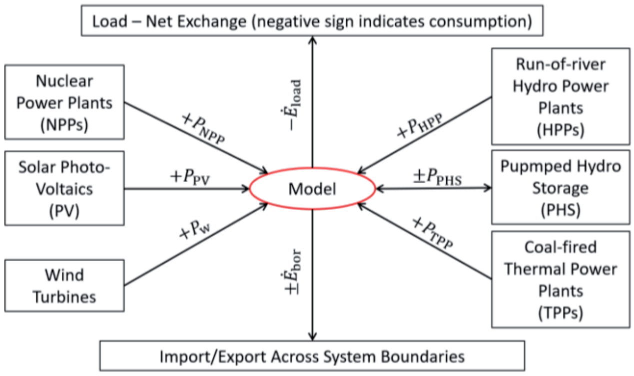

Figure 1. Basic operation of the modeled system

A. Energy Flow Modeling and System Discretization

Fig. 1. Basic operation of the modeled system

hourly resolution based on the available input data [3]. It should be noted that the approach remains adaptable to finer timescales, provided suitable input data resolution.

Each energy supply technology is modeled according to its characteristics, while consumer demand serves as a boundary condition and was adopted from the grid operator database [3]. Power plants and storage facilities are represented using zero-dimensional models, focusing on integral energy balances. These models leverage empirical correlations or black-box approaches, prioritizing computational efficiency over local process resolution. Such an approach is ideal for system-level studies where energy flow analysis and interactions between system components are paramount. The model is implemented in Python software environment.

B. Modeling Dispatchable and Non-Dispatchable Power Plants

Nuclear Power Plants

Nuclear power plants (NPPs) typically operate in baseload mode, maximizing power output within the constraints of their fuel cycle. Although modern NPPs allow load-following operation, economic considerations favor continuous operation at rated power [4]. Consequently, the model assumes constant nuclear power generation:

$$P_{\mathrm{NPP}}(\mathrm{t}) = \text{ const.} \tag{2}$$

It is important to note that next-generation nuclear reactors, including Small Modular Reactors (SMRs) and Advanced Micro Reactors (AMRs), demonstrate enhanced load-following capabilities, which are comparable to those of conventional fossil-fueled thermal power plants [4]. Accordingly, the model should be refined to accurately represent these advanced operational characteristics.

Wind and Solar Power Plants

Under Slovenian and European regulations, renewable sources such as wind and photovoltaic (PV) power plants receive priority dispatch [5]. Their power output is determined by the available resource potential:

$$P_{\mathrm{w}}(t) = P_{\mathrm{w,\,pot}}(t), P_{\mathrm{PV}}(t) = P_{\mathrm{PV,pot}}(t). \tag{3}$$

Consequently, these sources inject their entire available power (potential) into the system, irrespective of real-time demand-supply balance.

Hydropower Plants

Run-of-river hydropower plants (HPPs) provide flexible generation, rapidly adjusting their output to stabilize grid frequency and balance stochastic renewable fluctuations. Their power output is modeled using the fundamental hydraulic power equation:

$$P_{\mathrm{HPP}} = \eta_{\mathrm{HPP}}\, \rho_{\mathrm{H20}}\, \dot{V}_{\mathrm{r}}\, H_{\mathrm{r}}\, g, \tag{4}$$

where ρ_{H20} is water density, g is gravitational acceleration, $\dot{V}_{\mathrm{r}}$ is volumetric flow rate, H_{r} is the available hydraulic head, and η_{HPP} is the plant efficiency. Due to computational constraints, actual power potential of modeled HPP is determined using empirical data from a reference hydropower plant (HPP Arto-Blanca), employing a cubic regression model:

$$\hat{P}_{\mathrm{HPP}} = C_1 \hat{\dot{V}}_{\mathrm{r}} \hat{H}_{\mathrm{r}} + C_2\, \hat{\dot{V}}_{\mathrm{r}}\, \hat{H}_{\mathrm{r}}^2 + C_3\, \hat{\dot{V}}_{\mathrm{r}}^2\, \hat{H}_{\mathrm{r}} + C_4\, \hat{\dot{V}}_{\mathrm{r}}\, \hat{H}_{\mathrm{r}}^3 + C_5\, \hat{\dot{V}}_{\mathrm{r}}^3\, \hat{H}_{\mathrm{r}}, \tag{5}$$

where $\hat{P}_{\mathrm{HPP}}$is normalised HPP electrical power, $\hat{\dot{V}}_{\mathrm{r}}$ normalized volumetric flow rate, $\hat{H}_{\mathrm{r}}$ normalised hydraulic head and C_1 to C_5 are empirical model parameters. The quantities are normalized based on the modeled HPP nominal parameters.

The operation of run-of-river hydropower plants (HPPs) is modeled as a dispatchable source without storage, which represents a deviation from real-world conditions where such dams offer limited storage capacity [6]. In practice, run-of-river dams can provide hourly to daily energy storage; however, within the Slovenian energy system, this capacity is relatively small, typically allowing for only a few hours of storage. Given this constraint, storage effects were considered negligible and thus omitted from the model.

The power output from the HPPs was therefore determined based on instantaneous power potential and system demand. This approach ensures that HPPs do not inject power into the system when demand is absent, effectively simulating the diversion of excess river flow through overflow gates. The HPP model also imposes a minimum operational power limit of 40 % of nominal capacity, meaning that if the current power potential is lower HPP remains offline.

Thermal Power Plants

Coal-fired thermal power plants (TPPs) provide a significant portion of Slovenia's electricity. Their operation follows a trapezoidal generation profile, adjusting gradually to match demand variations. Technical operational constraints include: nominal rated power (typically for SLO ~542 $\mathrm{MW_e}$) ramp rate (typically for SLO ~10 $\mathrm{MW_e}$/min), operating range (typically for SLO ~42%–110% of rated nominal power). Although the technical constraints are well known, the real load variation of TPPs are primarily dictated by energy prices and contractual agreements rather than solely by fuel availability and technical constraints [7]. As economic factors significantly influence dispatch, predicting actual generation without them is not possible. Therefore, the model employs the time-dependent TPP generation profile

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based on the typical operation of the Slovenian power system, scaled by a factor k_{TE} , which defines the contribution of TPPs to total power generation:

$$P_{\text{TPP}}(t) = k_{\text{TPP}}\, P_{\text{TPP, SLO}}(t), \quad (6)$$

where $P_{\text{TPP, SLO}}(t)$ represents the data obtained from grid operator.

Gas Turbines

Gas turbines, operating on sub-hourly timescales, are unsuitable for the model's resolution and were thus included in imported energy flows.

C. Energy Storage Modeling

Slovenia's energy storage infrastructure comprises battery storage systems and Pumped Hydro Storage (PHS). While battery storage operates on sub-hourly timescales, making it unsuitable for this study, PHS provides bulk energy storage with high round-trip efficiency (~78%) [6].

The PHS model is based on the only PHS in Slovenia, PHS Avče [8] and incorporates several simplifications:

i. in pumping mode PHS operates only at nominal power;
ii. efficiency of individual system components, excluding turbomachine internal efficiency, remains constant;
iii. in turbine mode PHS operates between 30% to 100% of nominal power;
iv. head level variations due to reservoir depletion are neglected;
v. internal turbine efficiency is interpolated from empirical data for reference Francis turbine.

A detailed description of the PHS model is beyond the scope of this paper; however, its key characteristics are summarized as follows:

- the model incorporates a finite storage capacity that is charged and discharged during PHS operation;
- pumping efficiency is assumed constant, while turbine mode accounts for efficiency variations based on flow conditions and turbomachine characteristics;
- pumping operation is initiated only when excess energy flow in the system meets or exceeds the nominal pump power, at which point it operates at a constant nominal power.

D. System Energy Balance

The energy balance of the system is constructed in multiple steps, incorporating different power generation and storage components to ensure proper alignment of energy supply and demand at each time step. The steps flow:

i. Energy balance after priority dispatch power plants:

$$\Delta\dot{E}_{\text{sys,1}} = P_{\text{prod}} - \dot{E}_{\text{load}} = P_{\text{JE}} + P_{\text{w}} + P_{\text{PV}} - \dot{E}_{\text{Load}} \quad (7)$$

This step accounts for nuclear power and renewable sources (wind and solar) with priority dispatch.

ii. Energy balance after including thermal power plants:

$$\Delta\dot{E}_{\text{sys,2}} = \Delta\dot{E}_{\text{sys,1}} + P_{\text{TPP}}(t) \quad (8)$$

This incorporates the contribution of dispatchable coal-fired thermal power plants, which adjust generation according to demand and economic constraints.

iii. Energy balance after including hydropower plants:

$$\Delta\dot{E}_{\text{sys,3}} = \begin{cases} \Delta\dot{E}_{\text{sys,2}} + P_{\text{HPP, pot}}; & \text{if demand exceeds potential} \\ 0; & \text{if surplus power in system} \\ \Delta\dot{E}_{\text{sys,2}}; & \text{if partial HPP load is required} \end{cases} . \quad (9)$$

This step introduces run-of-river hydropower generation, balancing residual loads.

iv. Final energy balance after including pumped hydro storage:

$$\Delta\dot{E}^{\text{t}}_{\text{bor}} = \Delta\dot{E}^{t}_{\text{sys,4}} = \Delta\dot{E}^{t}_{\text{sys,3}} + P^{t}_{\text{PHS}}\left(\Delta\dot{E}^{t}_{\text{sys,3}},\, E^{t-1}_{\text{stored}}\right), \quad (10)$$

where P_{HPP} denotes the modeled PHS power, which can be positive (generation) or negative (consumption), depending on the system energy balance $\Delta\dot{E}_{\text{sys,3}}$ and the reservoir energy state E_{stored} at the previous time step $t - 1$.

This includes PHS operation. The final energy flow balance $\Delta\dot{E}_{\text{bor}}$ defines the required exchange of energy across system boundaries at given time step t, representing imports and exports.

III. Boundary Conditions

The modeled energy system is based on the current state of the Slovenian power system and selected development projections from the National Energy and Climate Plan (NEPN) [1]. Projections for 2040 were analyzed under two scenarios: Renewable and Nuclear Scenario (RS and NS).

The NPP size is based on Krško NPP expansion plans. According to [9] 1200–1600 MWe PWR is optimal for grid stability, with the model assuming a 1200 MW_{e} in NS. Continued operation of the existing unit (696 MW_{e}) is also foreseen in the model for both scenarios.

The boundary conditions for modeled TPPs assume an installed capacity of 542 Mwe ($k_{\text{TPP}} = 0.745$) for both scenarios, reflecting TPP Šoštanj, Unit 6.

The run-of-river HPP model is based on volumetric river flow $\dot{V}_{\text{r}}$ and hydraulic head H_{r}. HE Formin [10], Slovenia's largest HPP, was selected as the reference, with a nominal power of 116 MW_{e}. Hourly river flow data were interpolated from 2020 daily measurements at the Drava-Formin hydrological station [11]. Due to unavailable measured values, H_{r} was assumed to be 29 m, introducing minimal deviation given stable water level regulation in HPPs. The modeled 1276 MW_{e} hydropower capacity (Slovenia's existing HPP system: 1130 MW_{e}) approximates 11 parallel HE Formin units under identical hydrological conditions. While sufficient for this study, detailed analyses would require individual boundary conditions for each HPP. The same HPP capacity is assumed for both scenarios as foreseen in [1].

Two PHS units were modeled within the system, aligning with projections in [1].

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The energy potential of wind and solar power was modeled using meteorological data, with a single reference location selected for each. This simplification deviates from reality, as large-scale deployment at a single site is impossible, due to low energy density. Furthermore, conditions significantly vary by location. However, the reference sites were chosen for optimal wind and solar potential in Slovenia, inherently favoring renewable energy sources.

Wind speed data were obtained from the ARSO automatic meteorological station database [11] for Škocjan na Krasu and adjusted to turbine rotor height with exponential wind profile model. The reference wind turbine, Enercon 66/18.70 [12], was used with its technical characteristics to calculate the actual wind energy potential $P_{\mathrm{w,pot}}$. The model assumes 81 wind turbines (installed power 146 MW_e) in NS and 293 turbines in RS (527.4 MW_e), aligning with [1].

Similarly, solar power potential $P_{\mathrm{PV,pot}}$ was calculated using 2020 surface solarization data for Koper [13]. The model assumes 3.6 million panels (1,602 MWe) in the NS scenario, reflecting current installed capacity in Slovenia, and 18 million panels (8 GW_e) in the RS scenario, as projected in [1].

Hourly consumption data were obtained from the Slovenian grid operator's database [3], with 2020 as the reference year. Consumption was then scaled by 1.525 to align with the 2040 energy consumption projection [1].

IV. Results

A full discussion of simulation results is beyond this paper's scope; however, key results are outlined in Table 1.

Table 1. Results of the simulation for NS and RS

	NS	RS
share of RES in mix [%]	14	59
imported energy (neg. sign) [TWh]	-0.11	-1.91
exported energy [TWh]	3.19	6.94
net balance [TWh]	3.08	5.03
standard deviation of $\Delta\dot{E}_{\mathrm{bor}}(t)$ [kW]	420	1580
carbon intensity of energy mix [$kgCO_2eq/MWh$]	113	148

Across both scenarios, NPPs provided stable baseload generation, minimizing surplus energy while covering most demand. In contrast, wind and solar introduced large surpluses exceeding several GW_e (Fig. 2), requiring storage or substantial exports for system balance. TPPs operated at three discrete power levels (~0%, 40%, 100%), contributing to stability but responding slowly to demand changes due to thermal inertia, leading to minor but predictable surpluses.

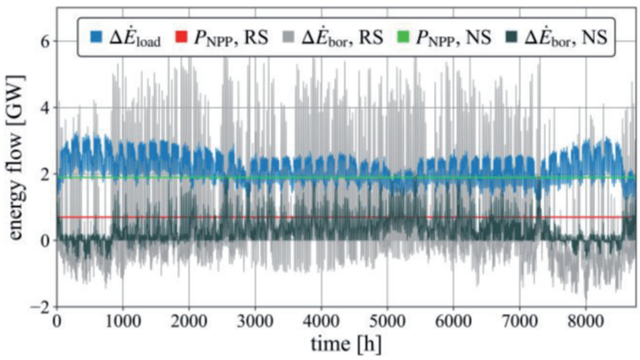

Figure 2. Basic operation of the modeled system

HPPs improved grid flexibility but lacked sufficient storage capacity to mitigate long-term variability. PHS helped stabilize high-power fluctuations but faced charging constraints, limiting its ability to absorb large renewable surpluses (>1 GW_e). Even additional PHS capacity did not significantly improve storage due to the same limitations. Table 1 quantifies fluctuation size through the standard deviation of the final energy balance $\Delta\dot{E}_{\mathrm{bor}}(t)$. The carbon intensity of energy mixes was calculated using data from Life Cycle Assessment studies summarized in [14]. Imported energy flows were assigned a footprint of 522 $kgCO_2eq/MWh$, based on gas turbine emissions [14]. This assumption is justified, as gas turbines are the most likely source of backup generation in interconnected energy markets even outside Slovenia borders [1]. To further assess NPPs' role in decarbonization, an NS variant excluding solar was simulated. In this case, annual imports increased to 0.30 TWh, while exports fell to 1.34 TWh (net balance 1.03 TWh), and carbon intensity increased slightly to 125.6 $kgCO_2eq/MWh$, demonstrating that a single conventional NPP can replace 8 GW_e of solar capacity, ensuring grid stability with minimal fluctuations while reducing reliance on backup plants, storage, and grid reinforcements, ultimately lowering energy costs while maintaining low emissions.

The environmental impact difference between scenarios is particularly evident in land use requirements: NS requires 2.4 km^2/TWh, while RS requires 9.1 km^2/TWh. The area was calculated based on [15]. This raises concerns about encroachment on protected areas (e.g., Natura 2000) [1], [15], with potential threats to biodiversity and ecosystem functions, including natural carbon capture capacity.

V. Conclusions

The analysis demonstrated that nuclear power ensures stable baseload generation, minimizing grid fluctuations and reducing reliance on extensive storage or exports. In contrast, high variable renewables introduced large surplus fluctuations (>1 GW_e), requiring costly balancing measures. Despite similar net energy balances, the nuclear scenario exhibited lower carbon intensity (113 vs. 148 $kgCO_2eq/MWh$) and almost 4-time lower land use, reducing pressure on ecosystems and biodiversity. A nuclear-only scenario, without solar, achieved carbon intensity of 125.6 $kgCO_2eq/MWh$, while maintaining a comparable import dependency to that of the NS, highlighting nuclear's undisputable role in decarbonizing energy supply and raising concerns about the feasibility and justification of renewable-only energy policies.

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