

THE STAKES OF NUCLEAR PLANNING OPTIMIZATION IN ELECTRIC SYSTEMS OPERATION WITH RENEWABLE ENERGY

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ABSTRACT :

The recent development of variable renewable technologies in electric systems calls for prospective work regarding, among others, the future optimal capacity mix as well as its related carbon footprint, security of supply, and overall costs. In the context of diminishing and fickle residual electric demand, each generating technology's operational flexibility will partly determine whether they shall participate in future decarbonized electric systems, and nuclear technology is no exception. Hence, assessing the available nuclear flexibility is crucial to evaluating nuclear power's economic and technical interactions and the newly-built renewables capacities. This paper identifies the underlying physical mechanisms that frame this technology's flexibility and operations and focuses its analysis on nuclear planning optimization, a structural characteristic of nuclear fleets. We develop a method to simulate this optimization to reflect how plants managers maximize their plants' availability during peak-demand periods. We compare two simulation hypotheses, one where the fleet's planning is optimized and another where the fleet's availability is considered constant, a standard practice in the energy systems modeling literature. The paper conducts a sensitivity analysis highlighting the links between the fleet's planning optimization, the relative share of nuclear and renewables in the capacity mix, and the simulation models' results. We find that modeling the nuclear fleet's optimization is of greater importance as the relative share of nuclear in the capacity mix is high. The planning's importance holds as renewables' installed capacities heighten, as the residual demand level decreases with higher volatility. Ultimately, this paper aims to highlight the potential benefits of modeling the fleet's planning optimization in simplified low-carbon electric systems with a significant share of renewable energy.

Keywords:

Nuclear energy; Flexible operations; Nuclear planning; Renewable energy integration; Unit commitment; Economic dispatch; Mixed integer linear programming

1. Introduction:

In the context of rising concerns surrounding climate change issues, most countries made commitments to reduce their electricity-generating mix's carbon emissions gradually, notably through massive development of variable renewables technologies like wind –onshore, offshore- and solar photovoltaic, concentrating solar power. It is a significant change in the supply-side of electric systems. Variable Renewable Energy (VRE) technologies are characterized by their high capital – negligible variable costs and their primary position in the economic "merit order"¹ dispatch to meet the electric demand. Adding the fact that their generation is highly dependent on weather conditions makes it optimal to prioritize them to meet the demand. Thus, the overall effect of developing high shares of variable renewables in the generation mix is to replace technologies such as coal, lignite, and even nuclear progressively as the primary means of generation of electric systems. Those technologies will need to operate flexibly to adapt to the variable renewable sources' inherent variability to remain valuable to the electricity system. In the context of deep decarbonization of the electric capacity mix, nuclear seems to be the only "baseload" technology that may play a role in future systems, alongside other systems components such as VRE, hydropower, storage facilities, demand-response, or low-carbon hydrogen.

Nuclear power plants typically operate in a "baseload" mode, meaning that they produce at their nominal power level most of the time. As nuclear fixed costs are high and variable costs low, it is economically optimal to use this operation mode. However, countries with a higher share of nuclear capacities may be forced to maneuver their nuclear power plants' output to balance electricity demand and supply. The case of the French electric system is blatant. As nuclear power plants represent 46.6% of the country's installed capacities in 2019 and 70,6% of its electricity generation [1], they frequently maneuver to participate in load-following or ancillary services. The nuclear fleet then provides a significant part of the current French flexibility requirements. Broadly, part of the installed nuclear fleet was initially designed to operate flexibly [2] or can be adapted to this regime through re-designing work [3]. The literature regarding nuclear flexibility, its ability to follow load, and the additional costs generated - wear of components, cost of retrofit and re-designing, fuel, and staff costs- is rich [3]–[12].

Nonetheless, most of the electric power systems modeling literature (e.g. [13]) still represents nuclear power as an inflexible technology, as noted by [11]. The studies that partially encompass nuclear flexibility typically represent the nuclear generation with assumptions such as ramping constraints or minimal stable power levels similar to other thermal technologies [12], [14]–[17]. Those modeling practices do not accurately represent nuclear power plants' flexibility specificities, driven either by neutron-transport constraints, primary circuit dynamics, or refueling strategies. Although reactors' designs differ across the world with varying underlying technologies (Pressurized Water Reactors, Boiling Water Reactors, CANada Deuterium Uranium, Fast-Neutron Reactor...), most of them are capable of flexible maneuvers[3]. This paper focuses solely on Pressurized Water Reactors as it is the current dominant nuclear design and is technically similar to the upcoming 3rd generation reactors.

The present paper is in line with recent works ([10], [11]) that highlight the impact of physics-induced plant flexibility modeling on the evaluation of future electric systems with renewable energy. While resuming the main constraints framing nuclear flexibility, our objective is to focus on the fleet planning optimization's impact on modeling results. The paper highlights the benefits of nuclear planning optimization to integrate VRE production in simplified electric systems. The paper's main contribution is the proposal of a novel Mixed-Integer Linear Programming model based on realistic refueling constraints of PWRs to simulate fleet planning optimization. The other main contribution is the case studies based on the French electric system's representative data, where we evaluate the benefits

¹ We refer here to the ranking of available generating units of an electric system, based on ascending order of marginal costs, aiming to minimize the overall generation costs of the system. Low marginal cost technologies then take priority over high marginal cost technologies in responding to the corresponding electricity demand.

of using fleet planning optimization to integrate renewable energy in a nuclear-based capacity mix. We find that using nuclear planning availability seasonality reduces the system's operational costs while decreasing energy curtailment and the overall CO₂ emissions of the system. However, the effect on market prices and plants' revenues is unsure.

The paper has the following structure: Section 2 resumes the technical constraints of the flexible operation of nuclear PWR. Section 3 presents a novel mathematical model to represent the nuclear fleet's planning optimization as well as the unit commitment and economic dispatch model Antares-RTE used in this paper. Section 4 resumes the different case studies and the model's results related to fleet planning optimization. The last section concludes on the main findings and discusses future work.

2. Flexibility limits of nuclear power plants:

2.1 Pellet-cladding interaction and ramping constraints:

Nuclear PWRs can modify their output level by changing the boric acid concentration, a neutron absorber, in their primary circuit or by changing neutron-absorbing control rod insertion levels. The underlying principle is the management of the fuel's chain reaction and the thermal energy level it produces by modulating the fission reaction rate in the core. Typically, as the boron concentration in the primary circuit increases or the insertion level of control rods in the fuel assemblies increases, the fission reaction rate decreases, thus lowering the thermal power produced, the steam production rate, and the electrical output of the power plant. [18] notes that, because control rods movement allows for faster and more precise power management, plant's managers favor it over boric acid regulation to operate flexibly. However, such power variations do not come without thermal and mechanical consequences.

The control rods' movement in the core creates thermal variations that influence fuel pellets and their surrounding claddings' volume. When inserting control rods, the temperature drops locally in the core, and part of the fuel's pellets and claddings contract. Reversely, when withdrawing control rods, the temperature rises locally, and part of the fuel's pellets and claddings dilate. Because the fuel pellets have a higher thermal expansion coefficient than their claddings, their volume is more sensitive to temperature variations. The power variations may bring the pellets and claddings in contact [19], creating mechanical stress that endangers the claddings' integrity, corresponding to a breach of the first containment barrier of PWRs. Although this Pellet-Cladding Interaction (PCI) phenomenon does not incapacitate production, it is common practice not to carry out flexible maneuvers following breaches in the cladding [6]. Other corrosion effects due to corrosive fission products may increase the occurrence of such breaches.

PCI's overall effect on the flexibility capabilities of PWRs is the limitation of their maximum power ramping rate as not to create excessive mechanic stress and keep the number of breaches within the design tolerance of fuel assemblies. This ramp level is highly dependent on the type of reactor, its irradiation cycle advancement, its operating mode, and the amplitude of the power variation [11], [20], [21]. Although most historical power variations do not exceed 0,5% of the plant's nominal power (P_{nom}) per minute [2], the theoretical ramping rate limits of PWRs range from 2% P_{nom} per minute to 5% P_{nom} per minute, and even 10% P_{nom} per minute for German PWRs [22]. Thus, even though the majority of the power simulation models literature does implement hourly ramping constraints to represent historical nuclear power variations (e.g., 25% P_{nom} per hour [11], [23]), PWRs do have higher ramping capacities that do not limit their flexibility at an hourly time step.

2.2 Xenon transients and boron concentration:

During the fuel fission reaction, two fission fragments are emitted. They then travel a short distance due to their positive charge and, once stopped, are considered as fission products. These are often unstable atoms that will give birth to other radioactive decay fission products. Some of those fission products are neutron poisons, meaning that they are undesired neutron absorbers that decrease the fuel's fission reaction rate. Three different neutron poisons significantly impact the core reactivity: Xenon 135, Samarium 149, and Gadolinium 157. Because Xenon 135 has the most considerable impact and is the only neutron poison limiting the plant's flexibility, we chose not to consider Samarium 149 and Gadolinium 157 reactivity defects.

Xenon is a fission product that mainly originates from the decay of Iodine 135, a fission product with a 6.7h half-life whose production rate is proportional to the fission reaction rate. Xenon 135 production in the core then evolves accordingly with the Iodine concentration in the core and "disappears" either by neutron capture or decay, with a 9.2h half-life.

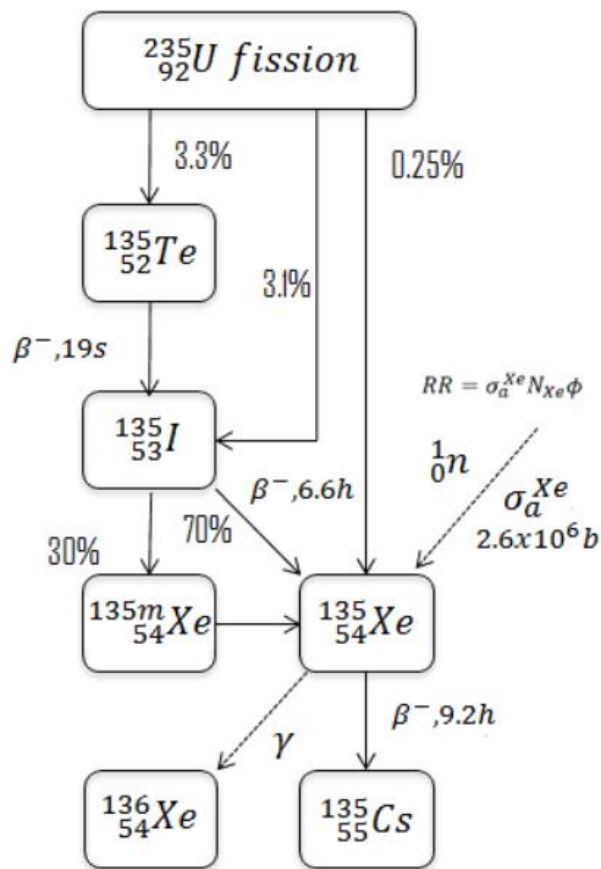


Fig 1: Xenon 135 evolution chain, www.nuclear-power.net, Data: JANIS 4.0/NEA

The fact that Xenon 135 originates mainly from the decay of Iodine 135 creates a temporal lag between the fission reaction rate variations and Xenon 135 concentration, resulting in a flexibility challenge that has to be managed [24]. As the reactor power rises, the I-135 concentration heightens until the reactor's new equilibrium state is reached. Xe-135 concentration lessens because of increased neutron flux, reaching a minimum three hours after the maneuvers' start, then goes back to an equilibrium state due to the accumulated I-135 in the core. Reversely, as the reactor power decreases, the I-135 production rate reduces, but the Xe-135 concentration heightens as it is still generated from the accumulated I-135. Because Xe-135 is a strong neutron absorber, such transients' management is a significant challenge to maneuverability, especially after large power variations. The reactivity

variations induced by the Xenon transients can nonetheless be overcome during most of the fuel's irradiation cycle, according to [10]. Thanks to the sufficient reactivity margin after refueling, it is possible to compensate for the Xenon reactivity defects through boric acid concentration adjustments or control rods' insertion level changes. [11] notes that if plant managers do stabilize their plant's output after maneuvering for several hours[2], it is done to simplify operations but is not related to technical limitations. However, at the end of the irradiation cycle, the core's reactivity decreases, and the reactivity margin becomes insufficient to compensate for Xenon transients effects without losing criticality [10], [24]. Indeed, the boric acid concentration in the primary circuit evolves following the reactivity decrease due to the progressive fuel's "burn-up", resulting in a decreasing margin for boric acid adjustments in the plant's primary circuit to control the fission reaction rate. Plants would then need to stabilize their output for multiple hours after maneuvering before ramping back to their initial level. According to [10], Xenon transients start to limit flexibility during the last 20% of the plant's irradiation cycle. Xenon transients' reactivity defects also explain why reactors need to remain closed for several hours after shutting down while in their irradiation cycle.

The achievable minimal stable power of PWRs then evolves according to the plants' advancement in their irradiation cycle [3], [26]. During the first two-thirds of the irradiation cycle, plants can operate flexibly up to 20% of their nominal power. Then, the achievable scope of maneuverability starts to decrease, and the plant's minimal power starts to increase linearly until the boric acid concentration reaches zero at the end of the fuel's irradiation cycle. The reactor can then only ensure primary and secondary frequency regulation. Afterward, the PWR enters an "extended-cycle" phase where flexible maneuvers are no longer possible, and the achievable maximal production capacity slowly decreases following the fuel's depletion.

2.3 Refueling strategies and nuclear planning:

Each nuclear power plant alternates between successive generation phases and planned outage phases linked to 1) the need to recharge fuel assemblies after the fuel's depletion, 2) the need for maintenance of components, and 3) security inspections to ensure that the reactor can operate safely. Those three elements are crucial for available flexibility capacity at the plant level throughout the year.

The generation phase duration depends on the reactor type, fuel cycle, and the fuel cycle's utilities' strategy. The irradiation cycle length that frames the generation phase's duration is defined as Effective Full Power Day (EFPD), which specifies how long reactors can operate at full power before their fuel's depletion. It ranges from 280 EFPD for older reactor designs such as CP0 reactors in France[27] to 500 EFPD and even 640 EFPD for newly-built reactors such as AP1000 [28] or EPR [29]. Those irradiation cycle lengths correspond to generation phase duration ranging from 12 months to 24 months, depending on the power plants' load factor. The outage phase's lengths depend on its type, either shorter refueling outage or longer refueling and maintenance outage. Additional regulatory outages may occur to inspect whether the nuclear plant meets safety requirements (i.e., decennial visit in France). Based on operational feedback, the outage phases represent approximately one-fifth of the irradiation cycle length [30]. This alternation between availability and unavailability is optimized beforehand to maximize the available nuclear generation through peak demand and the plants' load factor. The resulting schedule influences flexibility at two levels; the plant and the overall nuclear fleet. At the plant level, because of outages or fuel burn-up, there are some periods where generation and participation in flexibility requirements are impossible. At the fleet level, the addition of the combined electric system's reactors' availability and flexibility capacities define the fleet's overall generation capacity and maneuverability. The nuclear generation and flexibility availability is variable throughout the year, as illustrated in Figure below. This optimized schedule is the primary driver of long-term flexibility.

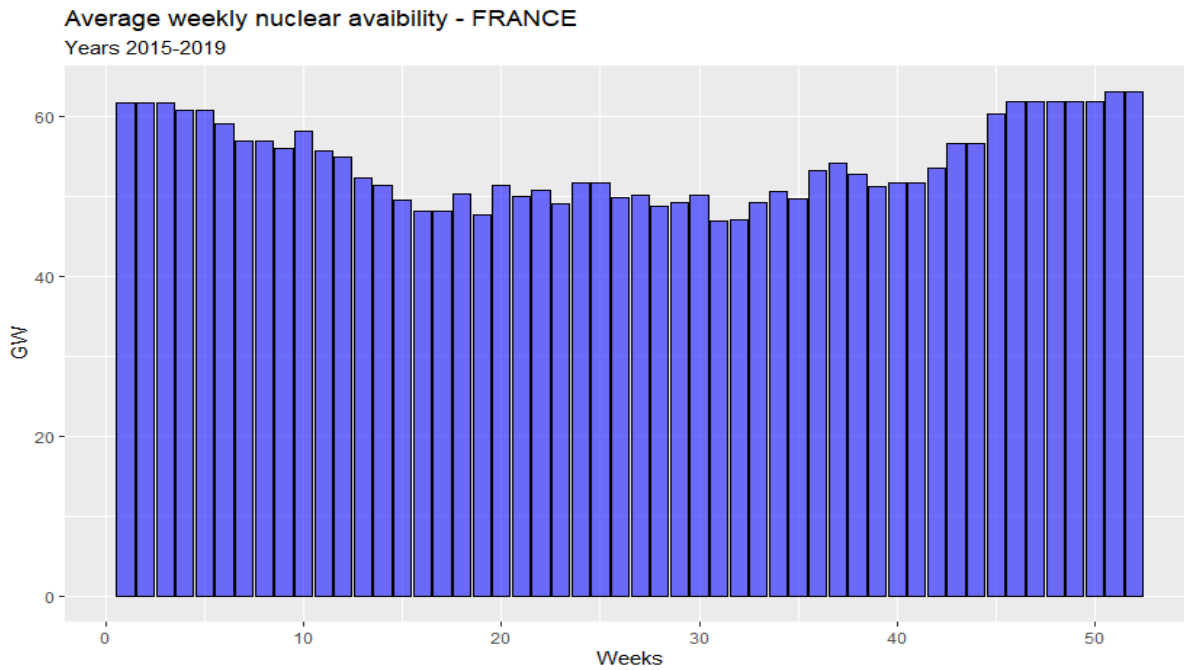


Fig 2: Average weekly nuclear availability, Years 2015-2019, France

Second, plant managers typically do not shut down every reactor simultaneously due to human resources and utility requirements constraints. Optimizing human resources for refueling and maintenance tasks and maintaining the electric system generating margins are of primary importance when deciding the fleet's outage schedule [31]. For example, in the US, a maximum of 22.5 GWe² of its 97.2 GWe³ fleet went offline simultaneously over the 2016-2020 period. In France, a country with a predominant nuclear fleet, a maximum number of 27 of its 58 reactors fleet went offline simultaneously over the 2010-2019 period⁴. Even though no physical constraints prevent reactors from shutting down simultaneously, it is crucial to ensure that a minimum share of the fleet is online to ensure that the optimized planning is realistic.

3. Unit-commitment (U-C) simulation models:

3.1 Mixed-Integer Linear Programming (MILP) planning optimization model:

As the plant's irradiation cycle typically lasts for more than one year, it is necessary to adopt an inter-annual approach to simulate the nuclear planning optimization. Using a benevolent system manager approach, we built a Mixed-Integer Linear Programming model maximizing nuclear availability when it benefits the electric system over several years. We consider this benefit equivalent to maximizing nuclear availability during peak electric demand periods. A higher nuclear availability during peak electric demand decreases peaking-plant use and drives prices low. The following heuristic model aims to represent the nuclear planning dynamic:

² STATUS OF U.S. NUCLEAR OUTAGES, EIA 2021, "<https://www.eia.gov/nuclear/outages/>"

³ World Nuclear Performance Report 2020. Produced by: World Nuclear Association. Published: August 2020. Report No. 2020/008

⁴ Computation by the authors, based on ASN data, <https://www.asn.fr/Contrôler/Actualites-du-contrôle/Arret-de-reacteurs-de-centrales-nucleaires>

$$\begin{aligned}
& \text{Maximize } \sum_{w=1}^T \sum_{i=1}^N \text{Demand}_t * Pnom_i * U_{it} \quad (1) \\
& \forall x \in [0; \text{MinimumOn}_i] : U_{i,t+x} \geq U_{i,t} - U_{i,t-1} \quad (2) \\
& \quad \quad \quad Y_i = \text{MaximumOn}_i \\
& \quad \quad \quad \sum_{y=0}^{Y_i} U_{i,t+y} \leq \text{MaximumOn}_i \quad (3) \\
& \forall z \in [0; \text{MinimumOff}_i] : U_{i,t+z} \leq 1 + U_{i,t} - U_{i,t-1} \quad (4) \\
& \quad \quad \quad \sum_{i=1}^N U_{i,t} \geq \text{NBOutagesLimit} \quad (5)
\end{aligned}$$

Nomenclature:

Indices:

t : index of time, week.

i : index for nuclear units.

Variables:

$U_{i,t}$: binary state variable for nuclear availability and outages, for nuclear unit i , time t .

Constants:

Demand_t : electric demand (MWh), time t .

$Pnom_i$: maximum power output (MW) for nuclear unit i

MinimumOn_i : minimum irradiation cycle duration (weeks) for nuclear unit i

MaximumOn_i : maximum irradiation cycle duration (weeks) for nuclear unit i

MinimumOff_i : minimum outages duration (weeks) for nuclear unit i

NBOutagesLimit : maximum number of nuclear units that must be online simultaneously

Eq. (1) is the model's objective function that maximizes the sum of the fleet's available reactors i times their nominal power $Pnom_i$ over a determined period. U_{it} is a binary variable equal to 1 if the reactor i is available at time t and 0 else. Demand_t captures the demand variability across the studied period. Eqs. (2), (3) frame the length of each plant's irradiation cycle, ensuring that each reactor is available during the entirety of its irradiation cycle length X_i and preventing potential overrun of its extended-cycle length Y_i . Eq. (4) frames the outages' duration. It ensures that each reactor is unavailable for MinimumOff_i timesteps after shutting down for refueling or maintenance. Eq (5) limits the number of nuclear units that can operate maintenance and refueling outages simultaneously.

	Nominal power (MWe)	Cycle Lengths (months)	Equivalent Full Power Days	Average availability factor	Minimum Outage duration (weeks)	Maximum Outage duration (weeks)	Minimum Irradiation cycle duration (weeks)	Maximum Irradiation cycle duration (weeks)
Unit	1000	15	400	79.1%	10	14	56	66

Table 1: Irradiation-cycle and outages lengths hypotheses

This paper considers that all reactors are similar, with a 1000 MW nominal power, 15 months irradiation cycle length, and 79.1 % availability factor, equal to french PWRs' availability factor since their industrial commissioning [32]. We chose to build our model at a weekly timestep to limit computational time. We hypothesized that each reactor shut down or start its irradiation cycle at the beginning of a week. The planning optimization timeframe chosen throughout the present paper is 18 years, spanning the 2001–2019 period.

3.2 MILP/UC electric system model:

The economic dispatch model used in this paper's scope is the ANTARES simulator developed by RTE. The paper by [33] provides a broad summary of the model. It is an open-source power system model that simulates the electric demand-supply equilibrium. The model consists of a unit-commitment program that determines the optimal economic dispatch of all the generating units in the system at an hourly timestep over one calendar year. The objective function minimizes the overall operational costs (variable, start-up, unsupplied energy costs) to meet the exogen hourly demand. Thus, the underlying discriminatory criterion between generators is the merit-order approach that ranks generators based on ascending order of short-term marginal costs. Apart from VRE sources, whose generation is considered exogen to the model, each generating unit's behavior is subject to UC constraints related to its maximum/minimum production capacity and maximum/minimum up/downtime. The ANTARES simulator includes each unit's availability planning, allowing modelers to adjust for seasonal plant's outage finely. A custom ANTARES solver solves the MILP problem, finding the optimal generation profile for each unit given its constraints, and computes the resulting market prices, CO2 emissions, spilled energy, and unsupplied energy of the modeled electric system.

The model integrates spinning reserves for thermal technologies in order to represent frequency regulation management. Aside from coal, gas, and fuel technologies, nuclear power plants contribute to automatic generation control signals sent by system operators and operating reserves. As existing reactors reserve 5-10% of their nominal capacity to frequency regulation and operating reserves, we consider that thermal plants reserve 10% of their nominal capacity for reserves.

This paper uses the 7.0.1 version, Accurate-Economy mode, whose mathematical formulation can be found in [34]. Contrary to version 8.0, version 7.0.1 does not optimize the system's capacity mix, meaning that this paper will focus on specific case studies whose installed capacities were determined exogenously. We consider that the environment is deterministic, with no uncertainties on future VRE production, demand level, thermal plants availabilities, and reserve requirements.

4. Case study and results:

4.1 Assumptions

The French electric system is the basis of this paper’s case studies. We chose this system due to the historically high share of installed nuclear power, meaningful feedback on nuclear fuel-cycle management, and data availability regarding renewables and electric demand. The French electric demand data used to optimize the nuclear planning range from 2001 to 2019 is the historical demand originating from RTE, the French Transmission System Operator. We exclude the year 2020 due to the demand decrease induced by the Covid-19 crisis that impacted economic activities. The paper builds VRE production profiles using actual capacity factors data from the renewables.ninja website, whose use is widespread in the electric simulation literature. Using capacity factors instead of actual generation profiles allows for multiple case studies depending on VRE integration levels. Although our heuristic model creates inter-annual planning for a specified fleet, we limit our electric system simulation to only a representative year. Following [35] that computed the sum of absolute difference of wind onshore, wind offshore, and solar PV capacity factors, we focus on the year 2006 as VRE capacity factors seem to be the most representative of French renewable production over the 2000-2017 period. Thus, electric demand, VRE capacity factors, and the nuclear fleet resulting from our model heuristic model, which the Antares Simulator uses to simulate electric system operations, are all 2006 data. This paper also focuses only on the isolated electric system of one country, meaning that the following case studies do not account for potential flexibility levers such as interconnections or sector-coupling mechanisms (EV charging, hydrogen production...). The installed technologies are limited, with only onshore wind, offshore wind, solar photovoltaic, nuclear, and natural gas. VRE’s and nuclear’s installed capacities are case-specific and fixed exogenously, whereas natural gas capacity is an output of each simulation, where gas capacity is dimensioned to ensure no Loss of Load. The considered natural gas technology is Open-Cycle Gas Turbine plants with a 38% electrical efficiency due to their high flexibility. Because this paper does not account for investments and fixed costs, the natural gas varying capacity does not impact the model results aside from gas being the last marginal unit that fixes the market price. Variable costs such as fuel costs are fixed over one year and originate from the report by the Nuclear Energy Agency (NEA): *The Costs of Decarbonisation: System Effects with High Shares of Nuclear and Renewables* [12].

Technology	Nominal capacity (MW)	Variable costs (\$/MWh)	Minimum Stable Power (%)	Minimum Uptime (hours)	Minimum Downtime (hours)	Start-Up Costs (\$/MW/start)	Reserve requirements (%)	Environmental impacts (gCO ₂ eq/kWh) – IPCC (2014)
Wind	-	0	-	-	-	-	-	11
Solar PV	-	0	-	-	-	-	-	41
Nuclear	1000	11.5	50%	8	24	500	10%	12
Natural Gas	300	96.11	25%	1	1	50	10%	490

Table 2. Overview of technology costs, flexibility and environmental impacts [12]

The paper constrains the flexible behavior of each thermal technology modeled. As mentioned in Section 2.1, ramping constraints do not limit nuclear or OCGT flexibility at an hourly timestep. Thus, we limit flexibility constraints to minimum up and downtime constraints only. We chose not to represent the minimal power evolution in this paper to focus our analysis on the effects of nuclear planning optimization. Implications of this assumption are discussed in Section 5. The other flexibility characteristics in Table 1 correspond to plants commissioned in 2020 [12].

4.2 Cases:

We simulate multiple cases that explore various capacity mixes and nuclear planning assumptions. The two case categories refer to two simulation assumptions: with or without heuristic nuclear planning optimization. The cases without nuclear planning optimization assume that nuclear availability is constant throughout the simulated year. This constant availability is equal to the average availability of the nuclear fleet in the corresponding heuristic planning case using our heuristic planning optimization model described in 3.1. The objective is to compare simulation results between those two core cases to evaluate the impact of nuclear planning optimization on modeling results. We include several sensitivity cases for each of those two core cases depending on the number of reactors installed and VRE penetration. Those two parameters are essential to the flexibility required of nuclear power plants. Each reactor fleet sensitivity cases represent various numbers of reactors, ranging from 20 reactors to 60 reactors. Each VRE penetration cases represent various VRE capacities, where VRE provides from 0 to 80 % of the total load if no curtailment occurs. We consider that the proportion of wind –onshore and offshore- capacities and solar capacities remain constant for each sensitivity case. We assume that this proportion is equal to the currently installed French VRE capacities[36]. Accounting for all VRE penetration, fleet size, and nuclear planning assumption cases, we simulate a total of $5 \times 3 \times 2 = 30$ different cases. Table 2 details the corresponding installed capacities for each renewable and nuclear sensitivity case.

VRE penetration scenario	Solar PV (GW)	Wind – Onshore and Offshore - (GW)	Nuclear capacity (GW)			Gas OCGT (GW)		
			20 reactors scenario	40 reactors scenario	60 reactors scenario	20 reactors scenario	40 reactors scenario	60 reactors scenario
0% VRE	0	0	20	40	60	68.03*	51.77*	35.49*
20% VRE	19.96	33.86				64.17*	47.91*	31.63*
40% VRE	39.93	67.72				62.83*	46.57*	30.29*
60% VRE	59.89	101.58				61.49*	45.23*	28.95*
80% VRE	79.85	135.44				60.15*	43.89*	27.61*

Table 3. Installed capacities for each simulated cases

*determined ex-post

4.3 Results:

This section presents key results for each of our planning optimization and VRE penetration cases.

4.3.1 Heuristic planning optimization results:

We computed a heuristic reactors' operating schedule for each of our nuclear fleet scenario cases – 20 reactors, 40 reactors, and 60 reactors (represented in Fig 4.). The heuristic planning allows for greater nuclear availability during peak-demand periods and lower nuclear availability during low-demand periods for each nuclear fleet scenario. Indeed, each heuristic planning scenario is positively correlated to the electric demand profile. Thus, our heuristic model does replicate the usual nuclear availability dynamics. Compared to the constant availability assumption, each heuristic planning is better correlated

to the demand profile. Secondly, we find that the impact of the planning optimization varies according to the size of the fleet. The profile gap between the constant availability assumption and the heuristic planning is more significant as the nuclear-installed capacity increases.

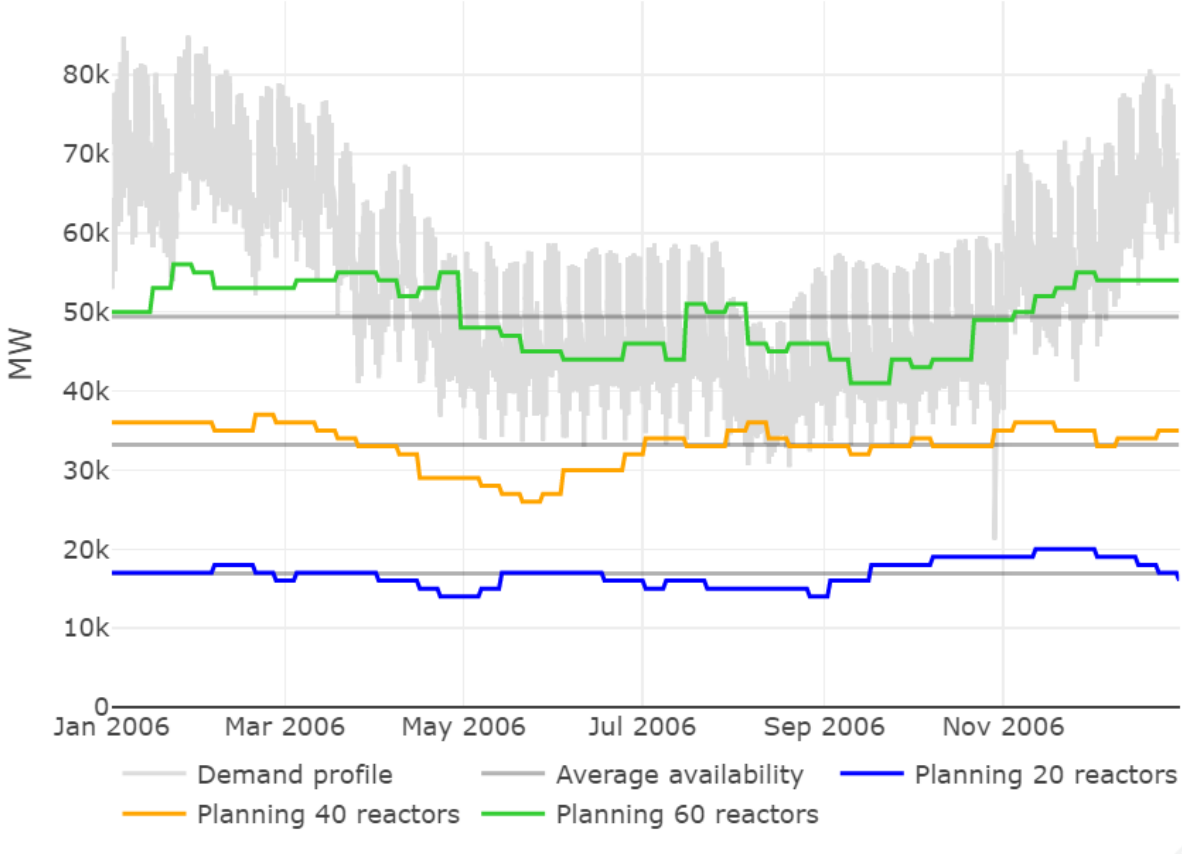


Fig 3. Nuclear availability for each nuclear fleet size scenario, resulting from the heuristic planning optimization model.

4.3.2 Simulation results:

Using the heuristic planning optimization discussed in 4.3.1), we simulate power system operation with several VRE penetration levels - 0%, 20%, 40%, 60%, 80% VRE penetration, and compare the simulation results to the corresponding simulations with constant availability assumptions.

4.3.2.1 Thermal commitment dispatch:

As the gross VRE production level is weather-dependent, its level is not sensitive to nuclear planning optimization. For brevity, we will not detail the gross VRE production level in this section and will focus on the thermal commitment dispatch. This dispatch evolves accordingly to each cases’ installed capacities, with higher nuclear production as the number of reactors in the mix increases. Conjointly, the gas production level decreases as it is the marginal technology of the “merit order”.

The impact of planning optimization on optimal thermal commitment dispatch varies depending on the VRE penetration level and the nuclear fleet size. In cases with low VRE penetration and a limited

number of installed reactors, planning optimization does not seem to impact the optimal commitment dispatch of thermal generating units, resulting in non-significant output changes. It may indicate that planning optimization is not of primary order when considering electric systems where nuclear power plants profit from a load factor near 100% (reported in Fig. 4). In cases with low VRE penetration and high fleet capacity, nuclear production moderately increases when the heuristic nuclear planning assumption is used. Conjointly, gas production decreases, meaning that the heuristic planning optimization resulted in diminished use of peaking plant to ensure the electric demand-supply equilibrium.

In cases with higher VRE penetration and fleet capacity, nuclear power plants are expected to maneuver more due to the decreasing level of residual demand. The resulting nuclear capacity factor then evolves negatively to VRE penetration and fleet size. In such capacity mixes, the impact of planning optimization seems to be a joint decrease of nuclear and gas production compared to cases that assume that the nuclear operational planning is constant (Table 3.). The fall of nuclear and gas gross production is more significant as the nuclear fleet's size increases. The planning optimization decreases not only the use of flexible peaking gas plants but also nuclear plants. It indicates that optimizing the nuclear operational planning decreases the need for flexible peaking plants to ensure the electric demand-supply equilibrium. On the other hand, the nuclear production decrease seems counterintuitive, as gas production decreases and the planning optimization allows for greater nuclear capacity during peak-demand periods. The annual commitment dispatch is insufficient to conclude on the origin of this decrease.

	0% VRE		20% VRE		40% VRE		60% VRE		80% VRE	
Technology	Nuclear	Gas	Nuclear	Gas	Nuclear	Gas	Nuclear	Gas	Nuclear	Gas
20 reactors	1.48E+08 (0.02%)	3.32E+08 (-0.01%)	1.47E+08 (0.02%)	2.37E+08 (-0.01%)	1.4E+08 (-0.12%)	1.52E+08 (-0.02%)	1.2E+08 (-2.87%)	9.79E+07 (0.25%)	9.87E+07 (-4.94%)	6.47E+07 (0.18%)
40 reactors	2.9E+08 (0.01%)	1.9E+08 (-0.02%)	2.81E+08 (0.31%)	1.03E+08 (-0.89%)	2.43E+08 (-0.61%)	5.22E+07 (-4.56%)	1.96E+08 (-4.91%)	2.83E+07 (-8.60%)	1.55E+08 (-8.65%)	1.61E+07 (-10.65%)
60 reactors	4.17E+08 (1.40%)	6.31E+07 (-8.38%)	3.65E+08 (1.93%)	1.96E+07 (-27.28%)	2.92E+08 (-1.39%)	7.31E+06 (-35.04%)	2.26E+08 (-7.58%)	3.36E+06 (-37.36%)	1.74E+08 (-12.45%)	1.84E+06 (-38.65%)

Table 4: Annual thermal energy dispatch – MWhe – in the heuristic planning cases and change relative to the constant planning cases (in brackets)

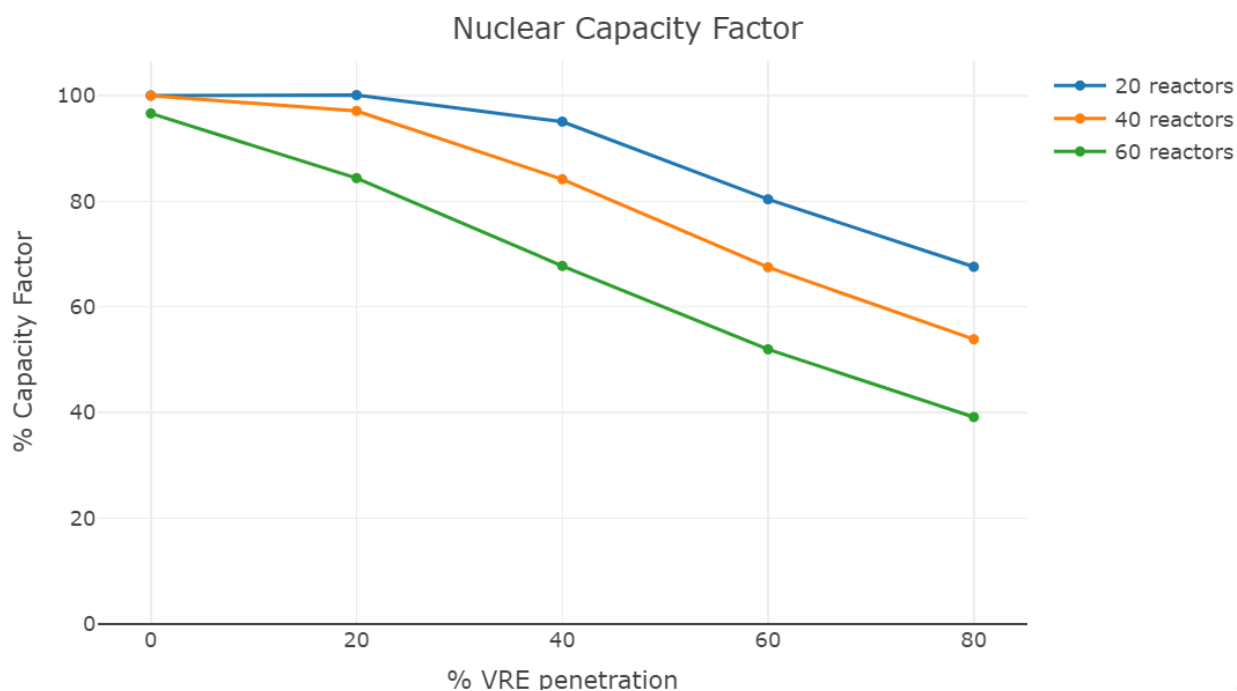


Fig 4. Annual nuclear capacity factor

4.3.2.2 Curtailment of renewables and nuclear:

The curtailed energy level of our simulated cases ranges from 0% of the total electricity production (e.g., 0% VRE penetration – 20 reactors case – both heuristic and constant planning assumption) to 18.01% (i.e., 80% penetration – 60 reactors cases – constant planning assumption). Such phenomena occur when the electric production is higher than the corresponding electric load because of an excessive VRE production or a lack of thermal plants flexibility that, at some point, cannot adjust their output. Regardless of the nuclear planning assumptions, the curtailed energy level positively correlates with VRE penetration levels that increase flexibility needs to ensure the supply-demand equilibrium. Another finding is that the curtailed energy level of our cases positively correlates to the installed nuclear fleet capacity, with a higher share of curtailed energy as the number of reactors in the simulated mixes increases. This negative effect of the size of the fleet on energy curtailment level is due to the replacement of flexible gas production by nuclear technology, whose flexibility is limited.

As we compare the heuristic and constant nuclear planning cases, we find that nuclear planning optimization decreases the wasted VRE energy share due to curtailment. In like manner to the thermal commitment dispatch, this impact is not significant in low VRE and nuclear capacity cases. In those cases, the significant gas production meets most of the flexibility requirements, resulting in marginal energy curtailment levels, and the benefits of nuclear planning optimization are null. Those benefits seem substantial as soon as VRE ensures a significant share of the electric demand and the nuclear capacity is higher than 20 GW. We evaluated the curtailment of nuclear technology, i.e., the production that is wasted as nuclear cannot reduce its output due to a lack of flexibility. We find that the level of nuclear production curtailment is lower as the nuclear planning profile is correlated to the electric demand. Hence, even though the gross nuclear production level is higher in cases assuming that the nuclear planning is constant (see. Section 4.3.2.1), this results in higher production curtailment. The gross nuclear production increase in the constant nuclear planning assumptions cases results from the curtailed production surplus. Finally, the combined decreases of VRE and nuclear curtailment highlights the benefits of nuclear planning optimization in renewables and nuclear-driven cases.

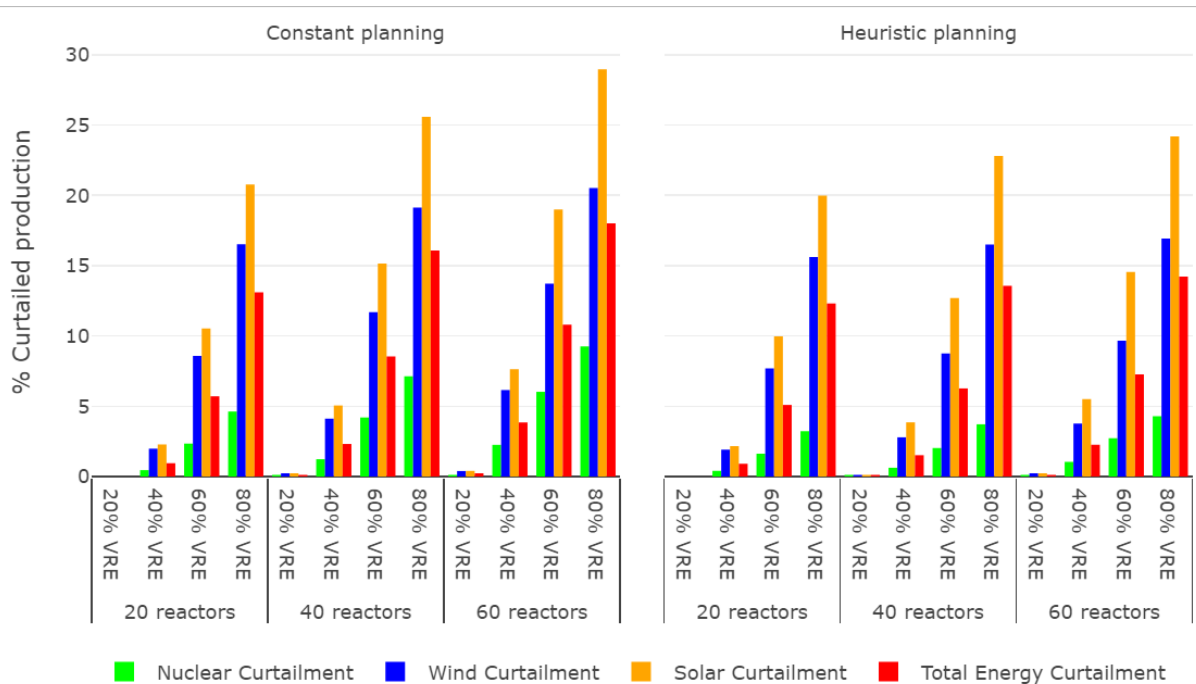


Fig 5. Curtailed energy for each VRE, nuclear, and nuclear planning assumption case

4.3.2.3 Systems costs and CO2eq emissions:

The overall effect of the heuristic nuclear planning is the decrease of the electric systems' operational costs in cases with a significant share of VRE penetration and high nuclear capacity. The first driver is the increasing share of the demand ensured by VRE technologies, whose operational costs are null, due to lower VRE curtailment levels. Other drivers are the decreasing gas production that is replaced by nuclear production and the decreasing total nuclear production, whose curtailment level decreases (see Section 4.3.2.1 and Section 4.3.2.2). The cost benefits derived from the heuristic planning optimization can be as high as a 15.38% cost decrease for the case with 80% VRE penetration and 60 GW nuclear capacity, highlighting the economic benefits of nuclear planning optimization as we consider electric systems with substantial shares of renewables and nuclear. Similarly to systems costs, the Global Warming Potential (GWP) of generating electricity, measured as CO2eq/kWh generated, decreases with the heuristic nuclear planning optimization in cases with 40 and 60 reactors, the relative decrease being as high as 22.42% in the 80% VRE penetration – 60 GW nuclear capacity case. The environmental benefits of the heuristic nuclear planning optimization increase with the VRE penetration in the 40 GW nuclear capacity cases, but not in the 60 GW nuclear capacity cases where the relative decrease stagnates once VRE penetration reaches 20%. On the other hand, the heuristic nuclear planning optimization does not influence the electric system's environmental impacts if the fleet capacity is low - e.g., cases with 20 reactors.

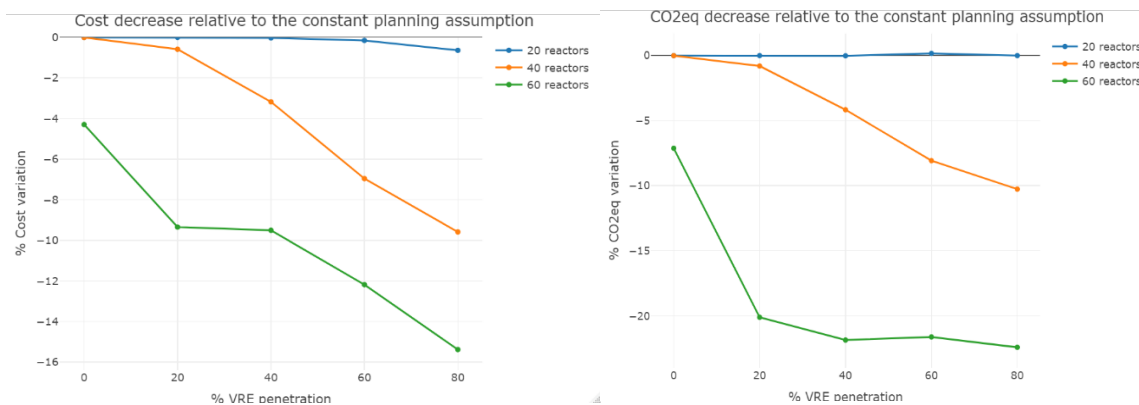


Fig 6. Heuristic planning cost and CO2eq changes relative to constant planning case

4.3.2.4 Market prices and revenues per technology:

The market price level evolves accordingly with the commitment dispatch of each case, with higher market prices in cases with higher gas production, which is the marginal technology based on the merit order. Thus, market prices decrease in cases with a higher nuclear capacity. The heuristic planning optimization does seem to have a limited effect on the average market price level, with slight prices decreases ranging from 0.3% to 12.25% of the average market prices in most cases (e.g., 40% VRE penetration – 20 reactors, 60%, 80% VRE penetration – 40 reactors and 0%, 40%, 60%, 80% VRE penetration – 60 reactor cases), but also increasing or stagnating prices in others. Because the average price per MWh decrease for all cases is 0.54\$ per MWh, we argue that the magnitude of this price decrease is not sufficient to conclude on the potential benefits of planning optimization on market prices.

On the other hand, heuristic planning optimization decreases the number of negative and null price hours. In periods of high VRE production and when thermal production cannot adjust its production level accordingly to the residual demand variations, negative prices may occur and reflect the thermal plants' willingness to avoid shutting down. Apart from the 0% VRE penetration cases and the 20 % VRE penetration – 20 GW nuclear capacity cases, where the number of negative price hours is null, the heuristic planning optimization does reduce the number of hours where market prices are either zero or negative. This result directly reflects the reduced level of VRE and nuclear curtailments that the heuristic planning optimization entails. Conjointly, the number of hours with peaking prices also decreases due to reduced gas production use, which is the primary driver of high market prices. For brevity, the following table details the market prices structure only for the 40% penetration – 60 GW nuclear capacity case, whose results are representative of renewables and nuclear-driven capacity mix cases.

Planning assumption	Average market price \$/MWh	Number of hours <0 \$/MWh	Number of hours >50 \$/MWh
Constant	24.24	2026	1196
Heuristic	21.27	1402	905
Relative change	-12.25%	-30.80%	-24.33%

Table 5. Market price data: 40% VRE penetration – 60 GW nuclear capacity case

As the heuristic planning optimization does decrease the number of negative price hours, it should increase the revenues of both VRE and nuclear technologies. However, this is not the case as we analyze the different case results, with varying VRE and nuclear revenue changes, positive or negative,

that do not reveal specific trends. It is then impossible to conclude on a potential effect of the heuristic planning optimization based on each technology’s revenue alone. To further our analysis, we investigate the composition of each technology revenue. In this paper’s simplified case studies, we argue that the revenues’ drivers are two-fold: first, the share of each technology output sold at low prices, driving revenues down, and second, the share sold at peaking prices, increasing revenues. If those two shares conjointly increase or decrease, their effects on revenues may balance out. We find that for each of our VRE penetration and nuclear capacity cases, the heuristic planning optimization decreases both the output share of all simulated technologies sold at low market prices and high market prices. Thus, for all low-carbon technologies –wind, solar and nuclear-, the revenue benefits stemming from less negative price occurrences are offset by the rarefication of peaking prices, driving the average market prices down. We illustrate this phenomenon using the following Table that highlights that even though each technology’s output share sold at negative prices lessens, it can be insufficient to increase the technology’s revenue. The contradictory effects of the decrease of negative price occurrences and the decrease of peaking price occurrences in all of our simulated cases also clarify why the heuristic nuclear optimization assumption has no definitive effect on the average market price level (see. Section 4.3.2.4).

Planning assumption	Solar			Wind			Nuclear		
	Revenues per MWh	Output share sold at <0\$/MWh	Output share sold at >50\$/MWh	Revenues per MWh	Output share sold at <0\$/MWh	Output share sold at >50\$/MWh	Revenues per MWh	Output share sold at <0\$/MWh	Output share sold at >50\$/MWh
Constant	11.11	43.95%	5.51%	15.11	36.19%	9.18%	26.68	15.03%	19.98%
Heuristic	10.82	35.78%	4.05%	13.73	25.89%	6.15%	24.19	8.21%	16.12%
Relative change	-2.64%	-18.60%	-26.46%	-9.11%	-28.47%	-32.96%	-9.31%	-45.34%	-19.32%

Table 6. Average revenues level and profile: 40% VRE penetration – 60 GW nuclear capacity case

In total, the impact of the heuristic planning optimization on market prices and technology revenues is ambiguous. The only simulated technology whose revenues decrease in all cases is gas due to its replacement by nuclear production. Regarding market prices, the heuristic planning optimization limits extreme price events, resulting in varying average prices per MWh changes. For VRE and nuclear profitability, the revenue benefits resulting from lower curtailment levels are offset by the decreasing peaking price share in some of our simulated cases.

5. Conclusions:

The present paper explores nuclear planning optimization benefits to integrate renewable energy in power systems such as wind and solar. We present a novel heuristic formulation of nuclear refueling and maintenance planning that frames nuclear operations, including irradiation-cycle and outage lengths. Using the resulting heuristic planning, we find that nuclear planning optimization does reduce operational costs, energy curtailments, peaking-plant use, and environmental impacts linked to electricity generation. Another key finding is that nuclear planning optimization’s relevance increases as the relative share of VRE and nuclear capacity in the capacity mix heighten, with low influence on

simulation results in cases with few reactors and limited VRE penetration and significant impacts in other cases. However, the impact of planning optimization on market prices and technologies' revenues is ambiguous, as the revenue benefits linked to the decrease of negative price occurrence can be offset by a decreasing number of peak prices.

The results found in this paper should nonetheless be contextualized. The numerical results are case-specific, and comparison with real-life power systems should be made cautiously, with assumptions such as gas prices heavily influencing those numerical results. Represented power systems are simplistic, with only one country represented, which eludes the physical network constraints that may reinforce energy curtailments. Most flexibility levers are also excluded, whether interconnections with neighboring electric systems, storage facilities, hydroelectricity, and demand-side response, all of which would likely decrease the flexibility value of nuclear planning optimization. Our objective in representing only five generating technologies – wind onshore, wind offshore, solar photovoltaic, nuclear, and gas CCGT - was to isolate the impact of nuclear planning optimization on the modeling results. Therefore, this paper's results should be extrapolated with care. We argue that nuclear planning optimization should yield similar benefits in power systems with significant nuclear and VRE capacity, where the nuclear availability seasonality would participate in VRE integration, reducing costs, environmental impacts, and energy curtailment. Future work could focus on the impact measurement of nuclear planning optimization in broader power systems with larger balancing areas, increased number of generating technologies, and better modeling of flexibility levers.

It is important to note that the proposed nuclear planning optimization model is a heuristic formulation of a complex process to determine when nuclear power plants begin their irradiation cycle or their outage phase. We consider that all reactors are similar, which is an unrefined representation of a realistic nuclear fleet composed of diverse power plants design with varying irradiation cycle lengths and nominal power. We also consider that the future is deterministic, with nuclear planning optimization spanning 19 years without any uncertainties. The maintenance and refueling operations duration are considered known beforehand, which is a gross simplification of real-life outages whose duration may randomly increase as operational difficulties arise. The inclusion of stochastic elements into the heuristic nuclear planning model would significantly impact the resulting optimal nuclear schedules. Such considerations are left for future work. As mentioned in Section 2, the need to schedule refueling and maintenance operations is not the only flexibility limit that frames nuclear adaptability to an increasing share of VRE. Phenomena that were not implemented in this paper's simulated cases, such as Xenon transients, prevent reactors from maneuvering at the end of their irradiation cycle and lessen the value of nuclear flexibility found in this paper. The analysis of the causal relationship between the nuclear planning optimization and the resulting maneuverability capacity of the fleet that depends on each reactor's irradiation cycle advancement would help evaluate the benefits of nuclear outage scheduling.

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