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A RELIABILITY-CONSTRAINED SCENARIO WITH A DECREASING SHARE OF NUCLEAR FOR THE FRENCH POWER SECTOR IN 2050

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ABSTRACT

This contribution relies on a prospective study of the French power sector up to 2050 using the TIMES model, combined with a reliability operating condition. To consider transient short-term power grid conditions, a reliability indicator related to the reserves of kinetic energy was defined and endogenized in the model to guarantee power system reliability under the implementation of a high share of variable renewable energy sources (VRES). For a declining share of nuclear inducing a high share of VRES, the pace of investments, additional back-up and flexible options to guarantee the grid's stability anytime were studied.

Keywords: Power generation, Nuclear energy, Power system reliability, TIMES model, France

NONMENCLATURE

VRES	Variable renewable energy source
RES	Renewable energy source
TIMES	The integrated MARKAL-EFFOM System
LTPM	Long-term planning model
DR	Demand response

1. INTRODUCTION

Unlike other sources of energy, renewable energy sources are widely available geographically. Beyond energy efficiency on the demand side, a high share of these sources employed in power generation is taken for granted to address tensions on resource scarcity, energy dependence, and environmental concerns by significantly decarbonizing electrical grids. However, in 2018, renewable energy sources accounted for 19% of final energy consumption in the world, of which more than half came from biomass and hydraulics. RES accounted for 24% of global electricity production [1]. France lags far behind in renewable energy development despite its hydroelectric potential (about 11% of electricity generation in 2018 [2]). Nevertheless, the French law on energy transition and green growth has set a goal of 40% renewable energy in final power consumption by 2030. To achieve this, a major change in the electrical system featuring an increase in renewable energy will need to be initiated. The integration of VRES represents a real challenge for the supply-demand balance and calls into question the reliability of the electricity grid. In this paper, a prospective analysis based on a scenario generated by the TIMES optimization model is used to study a decrease in nuclear capacity combined with a high share of VRES in the electrical mix. The explored scenario consists of a 50% reduction in nuclear capacity [3] between 2015 and 2035 (compliant with the French multiannual energy program), then a linear decrease in nuclear capacity between 2035 and 2050. The aim is to analyze how a nuclear phase-out and the integration of an increased renewable energy capacity up to 80% by 2050 would impact the French electrical system.

Based on a thermodynamic representation of power systems [3], an indicator related to kinetic energy stored within the power system has been developed in a previous work [4]. The study represents the power system's ability to maintain stability after a sudden disturbance. This kinetic reserve comes from the rotation of machines connected to the grid (assumed to remain synchronously working in spite of the disturbance) and compensates the unbalanced power exchanges throughout the power grid.

TIMES (The Integrated MARKAL-EFOM System) is a "bottom-up" techno-economic model generator (formalism) with a technology-rich basis for estimating energy dynamics over a long-term, multi-period horizon [5]. It is a partial equilibrium model belonging to the MARKAL family model, which means that it provides no feedback on sector changes in other economies. However, in most developed economies like France these impacts are of secondary importance [6]. The model is based on a reference energy system, which is a network of processes that are linked by their inputs and outputs, all constraints, and technical, economic and policy-based parameters to clearly analyze the relevance of optimal technology paths according to environmental and/or energy solicitations.

The reference energy system is depicted in Fig 1: It includes power exchanges with neighboring countries.

The objective function minimized by the TIMES model represents the total discounted cost of the system over the selected planning horizon. The components of the system's cost are expressed in each year of the study horizon in contrast to the constraints and variables related to the period. For every specified period, the model maximizes the total net surplus (suppliers and consumers) by respecting the defined constraints regarding the availability of resources, capacity transfer, etc. This choice results in a more realistic representation of the payments flows operating in the energy system.

The main assumptions of the model are listed below:

- The horizon of the study is 2013-2050 divided into 9 time periods of 84 time-slices each. A hypothetical week called Cweek (constrained week) has been added in the model to consider the inter-annual variability of the variable renewable energies. It represents a potential winter week with low solar and wind production and zero imports.

- Three flexibility options have been integrated into the model: demand-response (DR) (sub-hourly DR and hourly DR), storage technologies, and new interconnections (alternative current (AC) and direct current (DC)).

- The kinetic indicator, which is expressed in seconds, is introduced to quantify a system's kinetic inertia [7]. This indicator represents the time during which the stock of kinetic energy runs out completely to help recover steady-state conditions if the power generation is suddenly disconnected, or, conversely, the final consumption rushes to its peak value P_{peak}:

$$H_{\text{kin}} = \frac{E_{\text{kin}}}{\max(S, P_{peak} - S) - Q_{\text{stg}}}$$

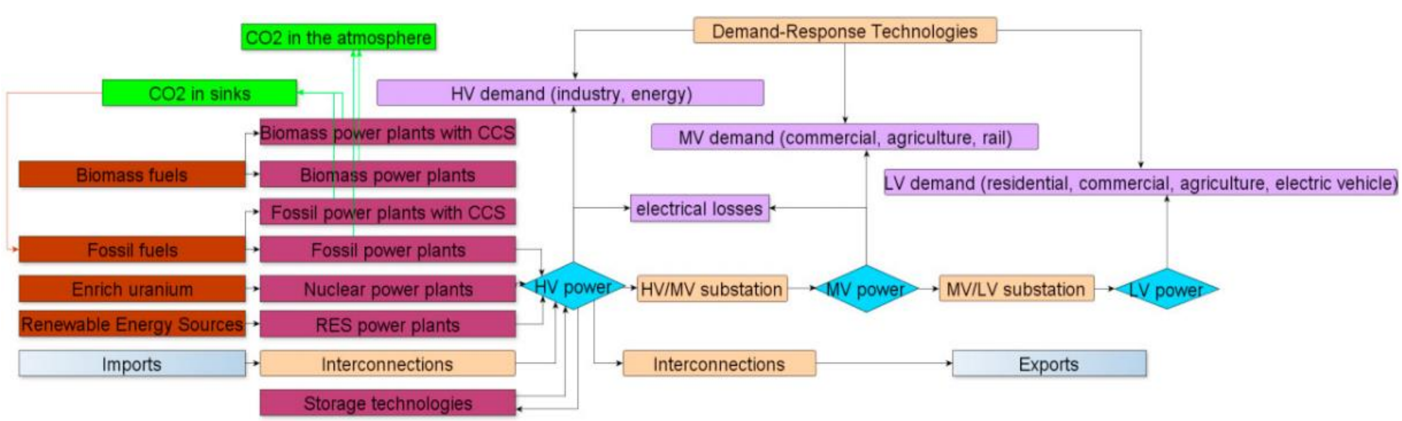

Fig 1: Schematic description of the reference energy system

H_{kin} quantifies the stored kinetic energy E_{kin} compared to the supplied apparent power S reduced by the dynamic storage compensation Q_{stg}, i.e. operating in less than 15 s. The higher the indicator, the more able the system is to maintain the balance after a perturbation. To ensure a continuum with the primary regulation, which typically operates within 15-30 seconds, it is mandatory to force H_{kin} to be greater than a certain value $H_{critical}$ (fixed in our study at 30 seconds) to stabilize frequency disruptions:

$$H_{\mathrm{kin}} \geq H_{\mathrm{critical}} = 30s$$

- In this paper, we do not consider the migration of demand towards electricity.
- In line with ADEME data [8], we limit the maximum installation of new capacities in 2030 and 2050 for several technologies, such as RES and storage technologies.

2. RESULTS AND DISCUSSION

In accordance with French multiannual energy planning, we make the nuclear capacity decline from 2025, dropping to 50 % of the 2013 level in 2035, then decreasing linearly until 2050 when the residual capacity is set at 10 GW. A second constraint is added to promote RES penetration and reach a capacity up to 80% by 2050 to avoid the substitution of nuclear with fossil fuel.

An increase in installed capacity can be observed in Fig 2. The total installed capacity for each technology over a period is equal to the sum of investments made by the model over past and current periods, and for technologies for which the life cycle has not yet ended. The increase in capacity is due to the short lifespan of intermittent renewable energies (20 years for wind energy and 25 years for solar photovoltaic) and their load factors (23% for onshore wind, 40% for offshore wind and 14% for solar photovoltaic). These load factors are very low compared to those of the conventional capacities they replaced (between 70% and 80% for nuclear power plants).

Investments in biomass and in coal plants are made starting from 2025. These plants are necessary to meet demand and maintain the reliability constraint on kinetic reserves when consumption rushes to a peak. The reduction in installed nuclear capacity is replaced by the implementation of solar and photovoltaic power plants. Imports double between 2013 and 2050, leading to a shift in power exchanges (Fig 3).

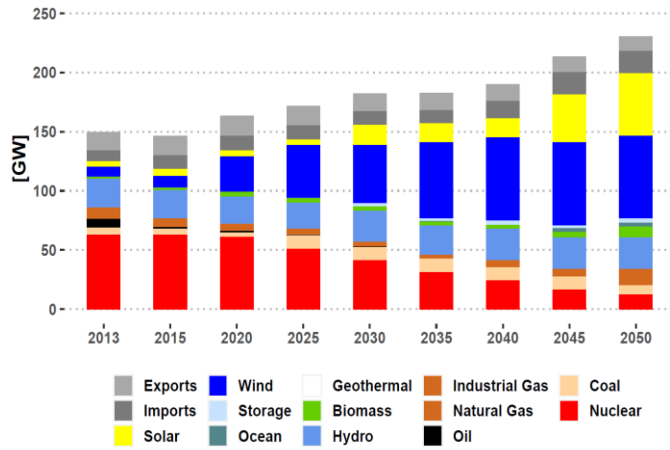

Fig 2: Evolution of the installed capacity between 2013 and 2050

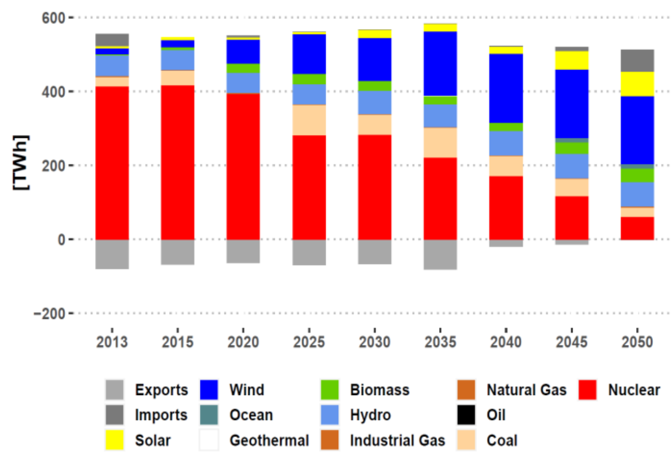

Fig 3: Evolution of the power generation mix between 2013 and 2050

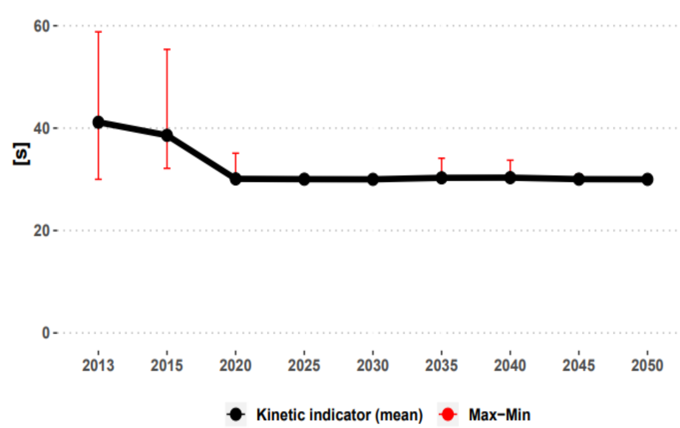

Fig 4: Evolution of the kinetic reserve between 2013 and 2050. The bars indicate the evolution of the minimum and maximum values observed during a year

Fig 4 displays the evolution of the kinetic reserve H_{kin} between 2015 and 2050. As the VRES share increases over the years, the kinetic reserve decreases to reach its minimum value by 2020. Thus, the integration of intermittent production sources will have to be anticipated. This question is particularly relevant in France, because the electrical system is very heat-sensitive (2.4 GW/◦C).

3. CONCLUSION

Using an endogenous kinetic indicator which represents a power system's stability with a long-term planning model, we assessed the impact of reliability-constrained scenarios with a decreasing share of nuclear up to 2050. The results show that, in the case of nuclear phase-out, France becomes a net importer of electricity. Furthermore, even without nuclear power plants, the system could require the installation of additional back-up or storage capacities to obtain more kinetic reserves and comply with stability requirements. This study could help clarify the issue of nuclear phase-out in the French electrical system [6].

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