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Reliability-constrained scenarios with increasing shares of renewables for the French power sector in 2050

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Abstract

The approach of this paper relies on a prospective study up to 2050 conducted by the TIMES model, combined with a quantitative assessment of the French power sector reliability. It is to take into account the short term power grid transient conditions in long-term prospective analysis. For this purpose, a reliability indicator related to the kinetic reserves has been defined and endogenized in the model in order to observe how the power system reliability may evolve in response to a high share of renewable energy source (RES) integration and stability constraint. It enables us to draw for reliability-constrained scenarios with high shares of RES, the possible shape of investments, additional back-up and flexible options needed to guarantee the grid's stability anytime.

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Keywords: Power generation; Renewable energy; power system reliability; TIMES model; France

1. Introduction

The integration of an increasing share of renewable energy sources (RES) in the power production is a crucial challenge in order to tackle resource scarcity, energy dependency and environmental issues. A sustainable development that would meet the needs of the present without compromising the ability of future generations to meet their own needs [1]. However, the RES are dominated by the variable renewable energy (VRE) (Solar, wind) and due to the high variability and lesser predictability of the latter; they could imperil the reliability of the power system.

In France, 75 % of electricity supply comes from nuclear power plants which make the French electricity generation structure unique. Moreover, nuclear power replacement will be the main power of the future as we saw in

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recent energy debate in France. As the power sector is characterised by low emission levels, the future electricity generation mix and the share of RES constitute major issues. The future mix for electricity generation and its relative shares have to be assessed in a context where there are numerous environmental constraints. This is why prospective analyses which could take into account the short-term dynamics of the power sector management with long-term would be very useful for decision-makers. Here, we focused on how to implement an important inertia of the power system to deal with contingencies. We take the example of an increase of the load (loss of a power plant or a sudden increase of the demand) (Fig. 1). The variations of the frequency are the image of the imbalances. When the production decreases or the consumption increases, the frequency decreases. Moreover, the frequency is related to the rotation speed of the machines. A decrease of the frequency means a decrease of the rotation speeds which will imply a decrease of the kinetic energy embodied in rotating machines. This kinetic energy (in red circle in Fig. 1) constitutes inertia of the power system to face a sudden disturbance before the start-up of the primary, secondary and tertiary regulations. The latter help the system to stabilize frequency disruptions.
We implicitly consider that the power system should be able to deal with hazards without relying on VREs, whose production is not completely foreseeable, cannot be adjusted to the demand and above all else with a limited participation to the system services like this kinetic reserves. It is essential to be able to represent this inertia of the system in our model.

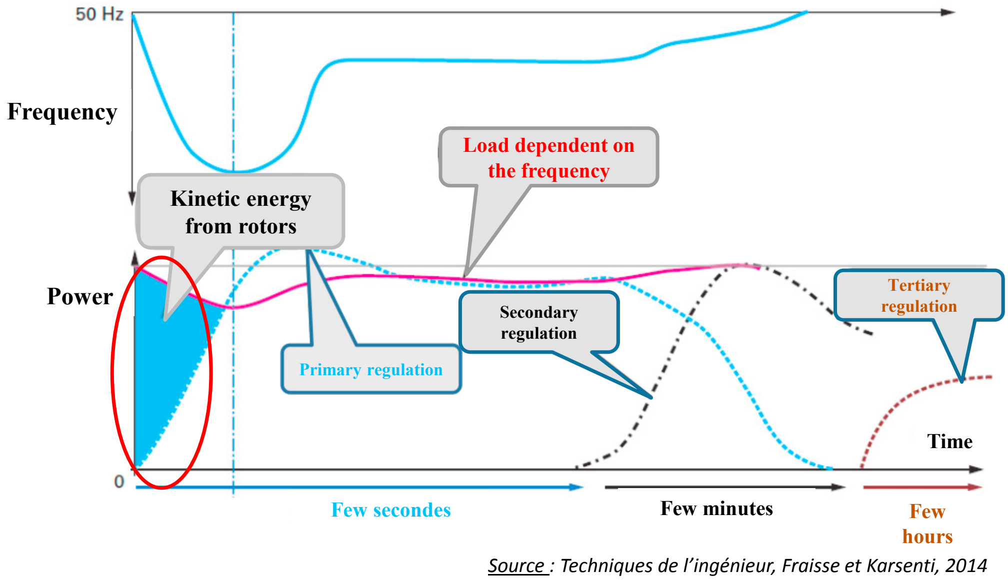

Fig. 1 : The functioning of the power grid facing a disturbance

One indicator related to kinetic reserves, has been developed based on a thermodynamic representation of power systems [3], which represent the power system's ability to keep working following a disturbance. This kinetic reserve comes from the rotation of turbines connected to the grid and compensates for unbalanced power exchanges before the start-up of the primary control [4]. This approach has been used in long-term planning model (LTPM) in the case of the Reunion island [2,5-6] as well as for France in post-treatment [4]. Previous results for France showed that 100% renewable energy scenarios could lead to a decrease by two third of the kinetic reserves [4]. Here we endogenized the kinetic indicator in the TIMES model for mainland France to test if an additional reliability affects the solution for high RES. We also test the effect of different RES ambition. Contrary to the previous work on France, this endogenization of the indicator will allow us to obtain directly from the model the different technology pathways to comply the reliability constraint of the power grid.

To do so, the linear formulation is changed to a lumpy investment option to take into account the granularity of the investments in our model in order to improve its rationality. Method for reliability is similar to earlier experiments for Reunion Island, that showed that a 100% with appropriate dispatch of local sugar cane do not jeopardize kinetic reserves [7]

In this paper, the question is to assess the change in terms of power system stability to a new energy model paradigm with less nuclear relying on the new French framework law on energy. Thus, instead of only presenting how the reliability is evolving according to the share of RES in the power production, we show the possible technology changes (installation of controllable means of production, storage capacity, increased trade with neighbouring countries, or demand-response options) necessary to prevent from decreasing reliability of the power system. The evolution of kinetic indicator is known as well at each time-slice of each period.

Section 2 succinctly describes, as a reminder to set the context, the structure and some assumptions of our model within TIMES as well the equation for the reliability constraint [8]; Section 3 present the possible evolution of the power mix and an analysis of the kinetic reserves with different RES penetration scenarios up to 2050

2. Methodology

2.1. The reference energy system

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 time horizon [9]. It is a partial equilibrium model belonging to the MARKAL family model, which means it provides no feedback on other economies' sector changes. However, in most developed economies like France, these impacts are of secondary importance [10]. It is based on a reference energy system which is a network of processes that are linked by their inputs and outputs, all constraints, technical, economic and policy based parameters to analyse clearly the relevance of optimal technology paths according to environmental and/or energy solicitations. Our reference energy system in our study where we considered France and the power exchanges with neighbouring countries is depicted in Fig. 2.

The objective function is the criterion that is minimized by the TIMES model. It represents the total discounted cost of the system over the selected planning horizon. The components of the cost of the system are expressed in each year of the study horizon (and even for some years off horizon) in contrast to the constraints and variables that are related to period. For every specified period, it maximizes the total net surplus (suppliers and consumers) by respecting the defined constraints regarding the availability of resources, capacity transfer, etc. This choice allows a more realistic representation of payments flows performed in the energy system [11].

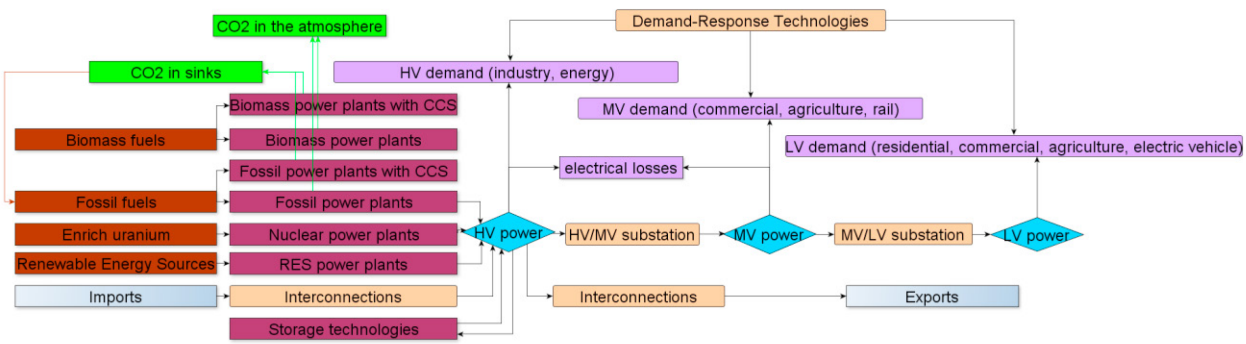

Fig. 2: Schematic description of the reference energy system [8]

It was developed to analyse and assess the possible consequences of various energy, environmental or legislative orientations with an explicit and detailed technology and energy carrier's representation. It is suitable for assessing long-term investment decisions in a complex environment.

Contrary to previous works in our research department on the same topic for France based on continuous model [8,12-13], we introduced the lumpy investment option discretization of the new processes). The accuracy of certain investment decisions could be problematic in some cases due to the linearity property of the TIMES model. For instance, the size of an electricity generation plant proposed by the model would have to conform to an implementable minimum size (it would make no sense to decide to construct a 50 MW nuclear plant). Then, the lumpy investment option available in TIMES insures that investment in technology ***k*** is equal to one of a finite number ***N*** of pre-determined sizes: ***0, $S_1(t)$, $S_2(t)$, …,$S_N(t)$.*** As implied by the notation, these discrete sizes may be different at different time periods. Note that by choosing the N sizes as the successive multiples of a fixed number ***S***, it is possible to invest (perhaps many times) in a technology with fixed standard size [9].

For such a scope with small-scale renewable power plants, the granularity of some investments may have to be taken into account to improve the robustness of the power sector's modelling even though it costs in terms of solution time (3693 new processes in discrete mode in comparison with 204 new processes in the continuous mode).

2.2. Main assumptions

In this section, the main assumptions of this model are listed below:

- The kinetic indicator, which is expressed in seconds, is introduced for quantifying a system's kinetic inertia [12]. This indicator represents the duration during which the stock of kinetic reserve runs out completely if certain percentage–typically 10%-of the production (named valmax in the equation (1)) is suddenly disconnected.

$$H_{cin,systeme} = \frac{\sum_{p \in connect} \left(H_{cin,p} * \frac{CAP_p}{PF_p}\right)}{Val\max * \left[\sum_{p \in connect} \frac{P_{mean,p}(t)}{PF_p}\right] - \sum_{p \in stg} P_{mean,p}(t)} \tag{1}$$

  We can see in the equation (1) that this indicator quantifies the kinetic energy stored compared to the called apparent power minus the dynamic storage compensation. More the indicator is bigger; more the system is able to maintain the balance after a perturbation. It is mandatory to be greater than a certain value called Hcritical, fixed in our study at 30 seconds.

$$H_{cin,systeme} \geq H_{critical} = 30s \tag{2}$$

  Thus our model will give the possible technology paths to meet the criterion (2) in order to keep the power system still reliable instead of only presenting how the reliability is evolving according to the share of RES in the energy mix.
- The horizon of study is 2013-2050 divided into 9 time periods of 84 time-slices each. A hypothetic week called Cweek (constrained week) has been added in the model to take into account the inter-annual variability of the variable renewable energies. It represents a potential winter week with low solar and wind production and zero imports.
- According to ADEME data [14], we implemented limit on maximal installation of new capacity in 2030 and 2050 for several technologies such as the RES and the storage technologies.
- We integrated three options for flexibility in the model: the Demand-Response technologies (DR) (sub-hourly DR and hourly DR), the storage technologies and the new interconnections (alternative current (AC) or direct current (DC)).

3. Results

We have set four scenarios of renewable energy penetration up to 2050 (Table 1). According to the French energy transition law [15], we constrained the nuclear power production at 50% of overall production from 2025 onward with RES penetration objectives of 27% and 40% respectively at 2020 and 2030.

Table 1: Description of the scenarios

Scenarios	Years	40EnR	60EnR	80EnR	100EnR
CO_2 emissions constraint	2013 - 2050	39 Mt	39 Mt	39 Mt	39 Mt

Nuclear prod. constraint	2025 - 2050	50%	50%	50%	50%
RES penetration objectives	2020	27%	27%	27%	27%
	2030	40%	40%	40%	40%
	2050	40%	60%	80%	100%

Thus, with the endogenous reliability indicator in the model, we observed that in Fig. 3, for the 40RES penetration objective, the model introduced more nuclear energy in the ending years in the case of the reliability-constrained scenario; thus a higher kinetic reserve of the system is obtained and the power mix gave by our model is complying perfectly the limit set for the reliability constraint of the system (Fig. 4 (a) (b)). **Indeed, the kinetic indicator has been divided by more than 10 with more RES penetration to reach 3 seconds in the 100EnR scenario without reliability constraint which means that the system has only enough kinetic reserves to face a sudden disturbance during this time (totally far to the limit of 15-30 seconds before the primary regulation will be available).**

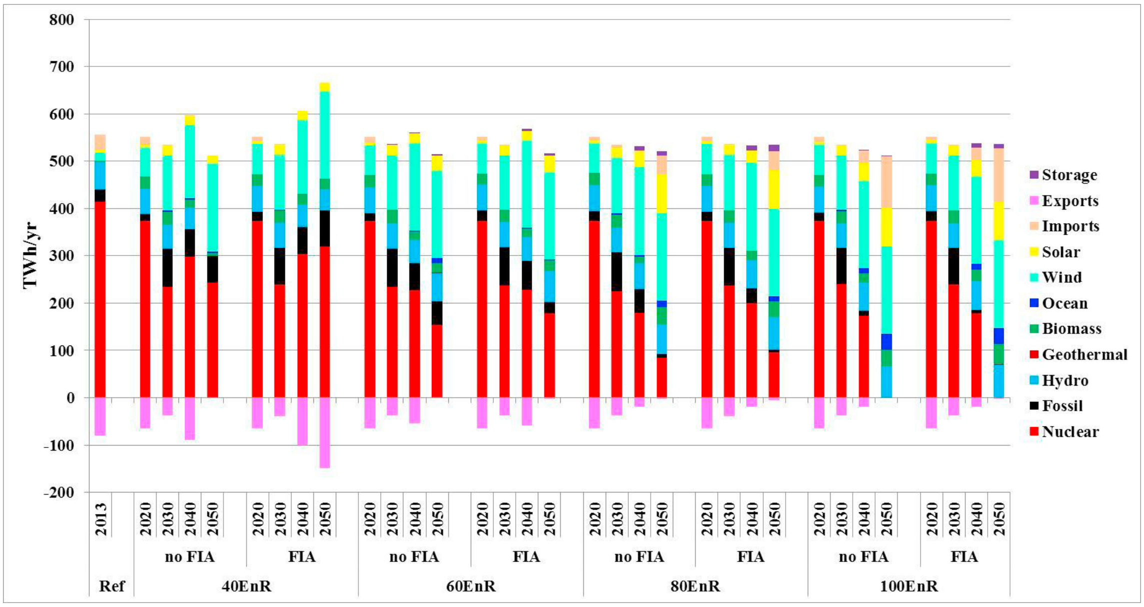

Fig. 3: Evolution of the power mix in the four scenarios (without the reliability factor “ noFIA” and with the reliability factor “FIA”)

With higher RES penetration in horizon 2050, the nuclear energy drops with time in the scenarios without reliability constraint which is however not the case with the presence of the kinetic constraint to achieve the reliability requirement. Wind is expected to be the dominant energy as we observed in all scenarios. **The system begins to introduce flexible options such as storage devices, more interconnections (more imports but less exports) from the 60RES penetration, despite that this introduction of storage is quite little which is more or less visible**. Fig. 4 (c) depicted the fact that, with the reliability constraint, the weight of the variable renewable energy (solar, wind) is getting lower due to the installation of technologies with more inertia such as nuclear, hydropower or biomass power plants (Fig. 3).

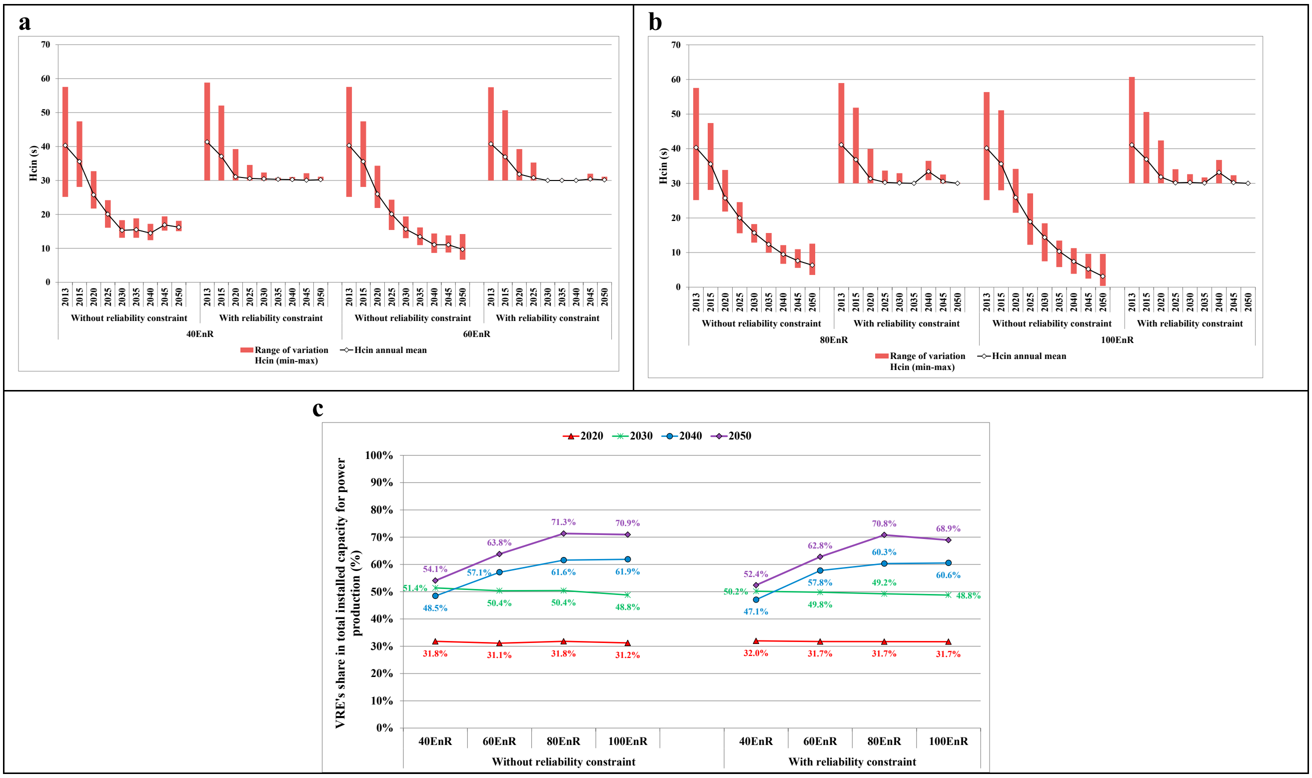

Fig. 4: (a) (b) Evolution of the deviation of the kinetic reserves from 2013 to 2050. The bars indicate the minimum and the maximum value of the kinetic indicator observed during a year. (c) Evolution of the share of the variable renewable energy in the total installed power in the four scenarios according to the presence of the reliability constraint.

At 100RES penetration, the system needs to use more imports as flexibility to satisfy the demand and reduce the share of the variable renewable to satisfy the stability requirement. **Moreover, this figure stated that VRE could not be higher than 70,8% in the total installed capacity without jeopardizing the power system.**

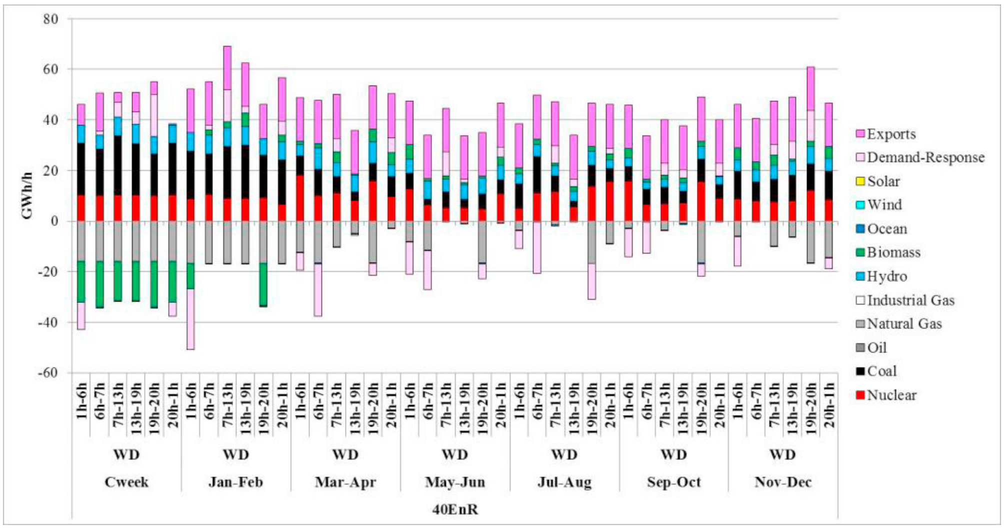

Fig. 5: The difference between the 40EnR scenario with and without the reliability constraint in hourly power production in 2050 for a typical week day for all time-slices (WD)

To analyse the impacts of RES on the power system, the model provides results on hourly power production. We could then observe the different model's arbitrage to comply the reliability constraint. In Fig. 5, it depicted the difference in hourly power production (here Week Day WD) between the 40EnR scenario with reliability constraint and without constraint in 2050. During the constrained week Cweek, natural gas and biomass are substituted with nuclear, coal and hydro which allow having more exports in the constrained scenario and a better reliability of the grid in 2050 as seen in Fig. 3. But in other months, biomass is one of the substitutes of natural gas. Besides, the demand-response option to postpone the consumption to higher production is still playing as well an important role to guarantee the reliability of the system in order to avoid an increase of the overall costs.

4. Conclusion

Using an endogenous kinetic indicator which represents the power system's stability with a long term planning model, we assessed up to 2050 the impact of reliability-constrained scenarios with high shares of renewables for the French power sector. The results show that the system could require the installation of additional back-up or storage capacity to get more kinetic reserves, and then to comply the stability requirement even up to 100 RES penetration objective. This study could help policy makers disentangle the issue of the high RES penetration in the French power system and to assess under which conditions it could evolve from a low-carbon nuclear-based to another one relying on a totally different production model.

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Biography

Nadia Maïzi is Professor in Applied Mathematics at the Ecole des Mines de Paris, and is running the Center for Applied Mathematics (www.cma.mines-paristech.fr) where she leads a team of 40 researchers and PhD students in the field of energy system optimization.
She is director of the Chair Modeling for sustainable development (www.modelisation-prospective.org) and is closely involved in sustainability and climate-energy initiatives and policies within the United Nations Framework Convention on Climate Change and the French government. She is member of the Expert committee.