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Manuscript_a2bf9f25b8e1027f485af3a118460006

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Energy Procedia 00 (2018) 000–000

Energy Procedia

ww.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

From centralized to decentralized power systems: The shift on finitude constraints

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Abstract

In this paper we address the consequences of the massive introduction of renewables for the future of power systems. Deriving a coherent approach suitable for long-term power systems analysis, we establish the link between future grid options mandatory to maintain technically plausible operation of power systems, physical factors and security of supply of fuels and sourcing of raw materials at an affordable price.

Keywords: Energy planning; Conventional power generation; Renewables; Transient reliability; France.

1. Introduction

Power systems are known to be one of the most complex human-made infrastructures involving millions km of line transmission and distribution as well as hundreds power plants. Production has to adapt in real time to consumption, which is strongly fluctuating and only partly predictable, taking into account technical, economical and environmental characteristics of power plants. In order to address the considerable stake of grid decarbonization, a battle between competing visions for the future of power systems blew between supporters of centralized and decentralized options.

In this paper we propose to address the consequences of each option in term of finiteness of non-renewable resources in a general context where according to EU analysis in the 20th century a fourfold growth in population led to a 12-fold increase in the use of fossil fuels and a 23-fold increase in the global extraction of ores and minerals [1].

In the next section, we present the TIMES model used for long term assessment and the indicators that we developed to evaluate the stability of the power system. The global condition for transient reliability is embedded within the model [2]. In the third section this theoretical framework is finally applied to a prospective analysis for the French power system for different scenarios of renewable energy penetration.

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2. Methodology

2.1. The reference energy system

TIMES (The Integrated MARKAL-EFOM System) is a "bottom-up" techno-economic model generator with a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon [3]. 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 [4]. 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. 1.

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.

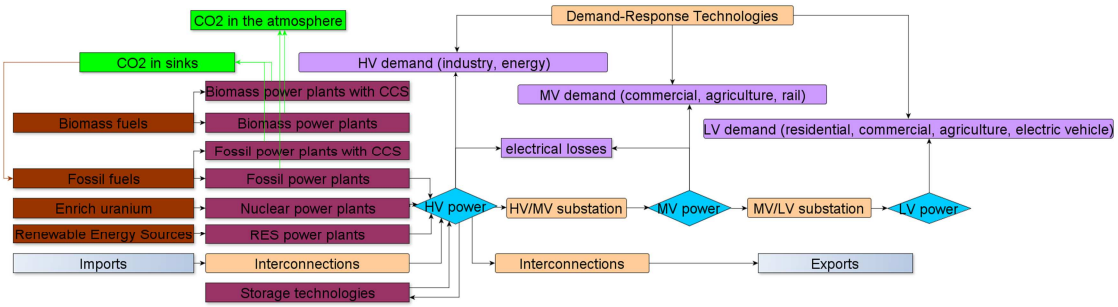


Fig. 1: Schematic description of the reference energy system [5]

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. Moreover, it integrates several constraints based on the following indicators in order to ensure the power system stability and reliability.

2.2. Main assumptions

In this section, the main assumptions used for the model TIMES are listed below:

- The kinetic indicator, which is expressed in seconds, is introduced for quantifying a system's kinetic inertia [2]. Providing synchronism is ensured over the whole grid [6], this indicator represents the duration during which the stock of kinetic reserve runs out completely to help recovering the steady state conditions if the power generation is suddenly disconnected, or, conversely, the final consumption rushes to its peak P_{peak}:

$$H_{\text{kin}} = \frac{E_{\text{kin}}}{\max\left(S, P_{peak} - S\right) - Q_{\text{stg}}} \quad (1)$$

The indicator (1) quantifies the kinetic energy E_{kin} stored compared to the supplied apparent power S minus the dynamic storage compensation Q_{stg}. More the indicator is bigger; more the system is able 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 enforce to the indicator (1) be greater than a certain value H_{critical} (fixed in our study at 30 seconds) to stabilize frequency disruptions

$$H_{\text{kin}} \geq H_{\text{critical}} = 30s \quad (2)$$

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 Renewable Energy Sources (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 [7], 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

According to the French energy transition law [8], scenarios of renewable energy penetration up to 2050 have been set (Table 1).

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%

The Fig. 2 shows the evolution of the French power mix from 2013 to 2050 with the reliability constraint for the BAU (business as usual) and the four renewable penetration considered scenarios. Whereas the reliability indicator (1) is almost satisfied for the BAU with and without any reliability constraint (Fig. 3 left), it is mandatory to perform constrained calculations since the RES penetration objective is high (Fig. 3 right) to keep an operable power system and prevent the collapse of the kinetic reserve for high share of renewable (*e.g.* division by more than 10 for 100%RES scenario without reliability constraint).

With an increase of the RES penetration objectives, a shift in power exchanges is observed in Fig. 2, exports decline till almost being non-existent in 2050 while imports are becoming greater reaching around one quarter of the power mix (around 125 TWh). The latter contributes more in the national power balance due to the decrease of the national production observed with the increase of the RES penetration. In these scenarios, nuclear power and, to a lesser extent fossil fuels, are substituted mainly by wind and solar which are getting to almost 37% and 16% respectively of the power mix in 2050. Besides, the system begins to introduce flexible options such as storage devices, more interconnections (more imports

but no exports from the scenario 60EnR in 2050) in 2040 from the 60% RES penetration, despite that this introduction of storage is quite little.

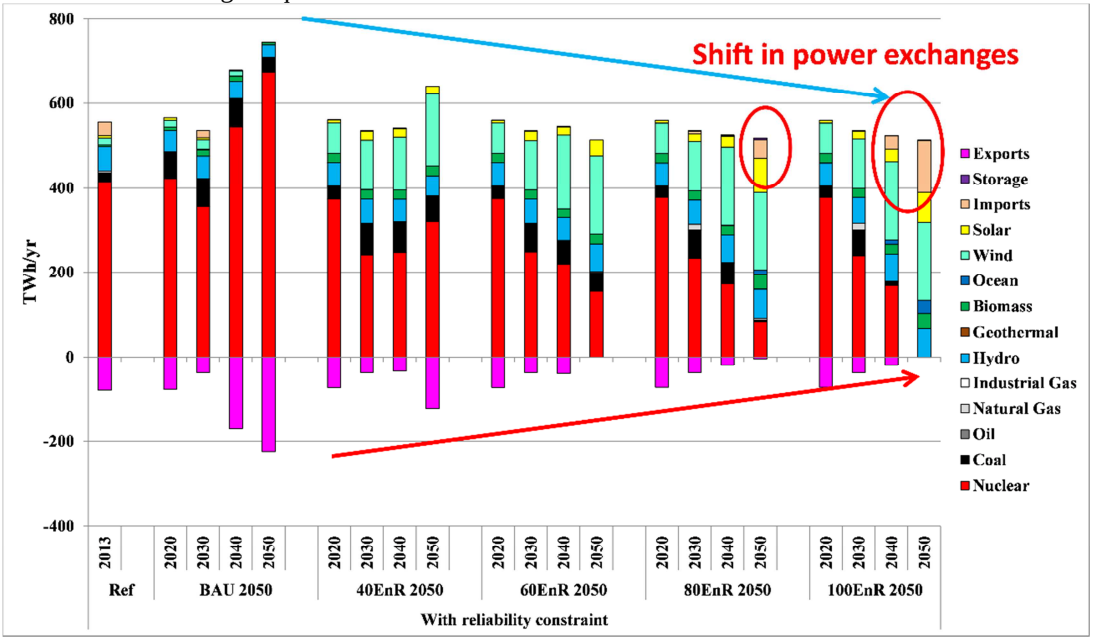


Fig. 2: Evolution of the power mix in the five scenarios with the reliability constraint. Notice the shift in the power exchange with the increase of the RES penetration objectives.

It means that in the 40EnR scenario or 100EnR, a new installation pace, respectively, of around 5.7 GW per year or around 7.6 GW per year is required between 2013-2050 (Fig. 4) which is huge in comparison with the past French nuclear installation pace of 2.6 GW/year (63 GW during 24 years) or the past German wind installation pace of almost 2 GW/year in around 25 years (50 GW Wind installed in 2016) [9]. Grid options coping with renewable penetration scenarios are decentralized options, based on massive and dispersed introduction of intermittent production of electricity forward, which could make power system management even more complex. In order to enable system operation and to compensate the lack of reliability, this system requires ICTs investments for monitoring, enhanced control-command to handle flexibility and provide agility, and extra devices to compensate kinetic energy and reactive power. As this system design induces high level of power auto-consumption, more structural and functional material and ore extracted and/or recycled, its viability is constrained by the limitation of physical factors and security of supply of raw materials at an affordable price.

Conversely, for the BAU, centralized grid option limitations mainly come from primary energy resources availability. Indeed, reliability of transmission and operation conditions are intrinsically embedded in conventional power plants (*i.e.* kinetic energy-induced transient stability (Fig.3 left) and reactive power-induced transmission).

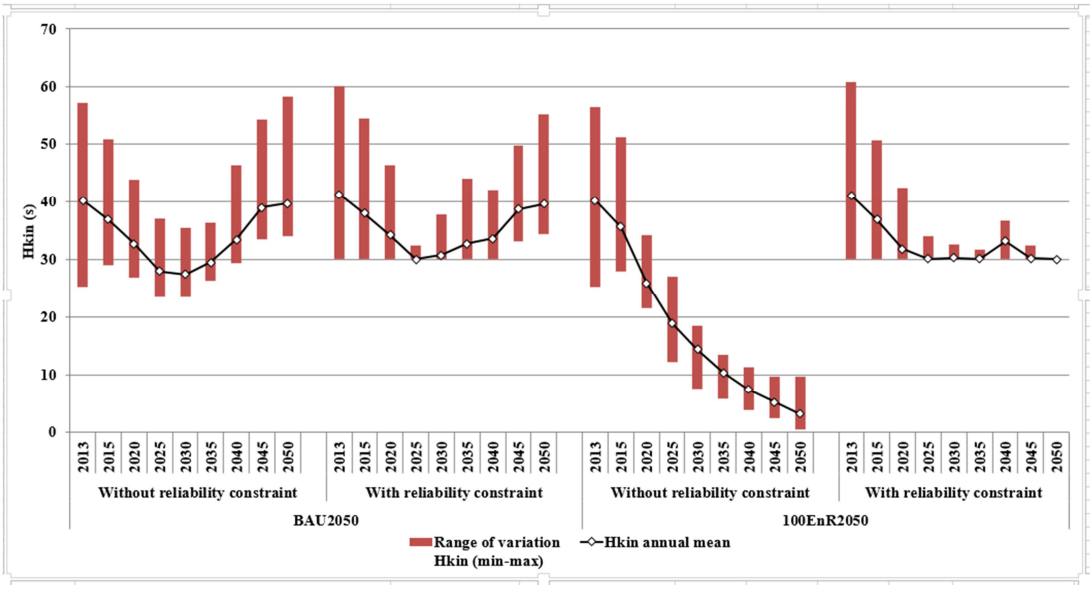


Fig. 3: Evolution of the deviation of the kinetic reserves from 2013 to 2050. The bars indicate the minimum and the maximum value of the kinetic indicator (1) observed during a year. Notice the collapse of kinetic reserve for the reliability-unconstrained 100EnR scenario.

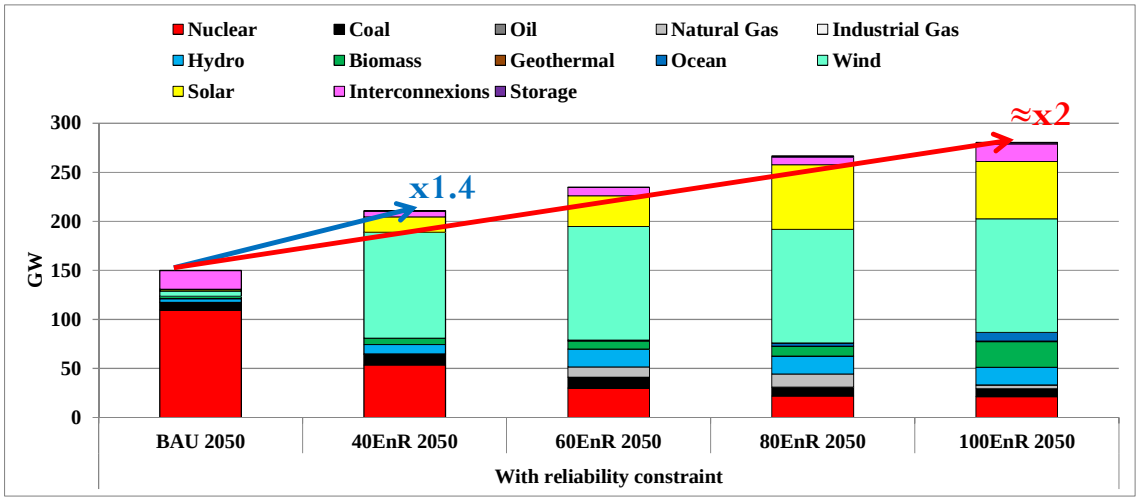


Fig. 4:: Evolution of the cumulated new installed capacity for the scenarios with reliability constraint between 2013-2050.

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. From the results presented so far, high variable renewable energy penetration seems technically feasible without jeopardizing the reliability of the French power system. But:

- More implications of the flexible options, *i.e.* the Demand-Response, the storage technologies and the interconnections or substitute or additional plants, to satisfy the reliability constraint anytime by providing extra inertia to the system;
- It sheds light on the importance of power exchanges with neighbouring countries and therefore the question on their energy mix;
- It leads to a shift in the trade balance with higher RES penetration;
- The scale of the new capacity installation paces observed in the results with an increase of the RES penetration objectives, shows that the French power system would require a profound change but above all else a very important upstream planning;
- The achieving of high share of renewables, mainly dominated by VREs, would then need a massive installation of new capacities, especially since the RES penetration objectives are more ambitious.

Eventually this study has demonstrated that shifting from the current centralized grid option on which is based the BAU scenario assumptions to high share of renewable energy penetration option for the power mix in France with decentralized grid will not solve the question on availability and subsequent dependency on resources with a shift from fuel supply to structural and functional material sourcing.

Acknowledgements

This research was supported by the Modeling for sustainable development Chair, led by MINES ParisTech, Ecole des Ponts ParisTech, AgroParisTech, and ParisTech; and supported by ADEME, EDF, GRT Gaz and SCHNEIDER ELECTRIC.

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