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Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis

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HIGHLIGHTS

- Combination of thermodynamic framework and energy-planning model.
- Short-term dynamic of power systems in long-term prospective studies.
- Approach applied to renewable penetration in the French power system.
- Major role played by dispatchable power plants, imports and demand-response.
- Renewable energy penetration may jeopardize power system reliability.

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ABSTRACT

This paper explores the conditions under which renewable energy sources (RES) penetration could jeopardize power system reliability, as well as which flexibility options could help integrate high levels of RES. For this purpose, we used an energy-planning model from the TIMES family, which provides a realistic representation of power systems and plausible options for their long-term development, completed by a thermodynamic description of power systems to assess their reliability. We applied this model to the case of France and built contrasted scenarios, from 0% to 100% renewable energy penetration by 2050. We also tested different assumptions on Variable Renewable Energy (VRE) production, imports, demand flexibility and biomass potential. We show that high renewable energy penetration would need significant investments in new capacities, new flexibility options along with imports and demand-response, and that it is likely to deteriorate power system reliability if no technologies dedicated to this issue are installed.

1. Introduction

1.1. Context of the study

Renewable energy sources (RES) have been developing rapidly since the early 2000s. Today, countries all over the world have set penetration targets for these energy sources in order to combat climate change, anticipate fossil resource depletion and solve energy dependency issues. For instance, the European Union set an objective of 20% renewable energy in final energy consumption by 2020 [1], recently extended to 27% by 2030 [2]. Many states in the United States (US) have implemented Renewable Portfolio Standards (RPS) that require suppliers to provide a minimum load using eligible RES [3]. In France, RES must account for 23% of final energy consumption in 2020 and 32% in 2030. The targets are respectively 27% and 40% in the power sector [4]. In the longer term, typically 2050, several countries or regions have designed roadmaps to achieve greenhouse gas (GHG) emissions reductions of up to 80% compared to 1990 levels. According to these roadmaps, the power sector could play a major role in two ways: first, the GHG emissions reduction target could be higher than for other sectors (between 90% and 100%) and secondly, a high share of energy demand from other sectors, such as transportation, could be provided by electricity in the future [5].

Since RES are GHG-emission-free (with the exception of biomass combustion), they could represent a significant share of power production in 2050. However, some RES rely on external weather conditions: these are called Variable Renewable Energies (VREs). They do not offer the same service as conventional generators and, as consequence, high VRE penetration levels, if not carefully anticipated, could hinder power system management and strongly push up power supply costs [6]. This is the main issue addressed in this paper.

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1.2. State-of-the-art on the impacts of VRE penetration on power systems

In order to perform relevant analyses of the evolution of power systems integrating VREs, we need to consider their specific features and the options that could help improve their integration. The potential impacts of VREs on power systems can be classified according to the temporal scale with which they are linked. Deane et al. [7] gave an exhaustive presentation of the different time scales relevant for power system security concerns and showed how VREs could weaken power system security on each of these time scales. They claimed that these scales should be analyzed together when evaluating the impacts of VRE penetration on power systems, and they proposed a methodology for coupling a Long-Term Planning Model (LTPM) with an Optimal Dispatch Model (ODM) to address this issue. LTPMs determine the cost-optimal pathway to reach certain objectives in the medium or long term. They minimize the overall cost throughout the studied period, taking into account both investments and dispatch, generally performed in a stylized way: power plants are aggregated into a single process for one technology, and hours, days and months are aggregated into a more or less small number of *time slices* (TS) in order to limit the computational time of the model as well as the number of assumptions to be made. In contrast, ODMs generally perform a more accurate dispatch, but only for one year and for exogenous assumptions on installed capacities. ODMs are based on an hourly representation of the supply–demand balance (or infra-hourly) taking into account technical constraints such as ramping constraints, minimal power output, and startup costs. They solve what is known as the Unit Commitment Problem (UCP). Despite the use of these two models, the authors explained that the very short time scale, which covers the ability of power systems to cope with sudden disturbances (typically the loss of an element or very quick variations of demand and production at a second or minute scale), named power system stability, was not addressed in their study and would require a third tool as well as many data. One goal of the present study, and the model we have developed, is to give insights into power system stability in LTPM without explicitly representing the very short-term dynamics involved in this issue.

Generally speaking, there are currently three ways of tackling VRE integration concerns in LTPMs:

1. Improving the representation of VRE variability directly in LTPMs with an appropriate choice of the temporal description.
2. Coupling an LTPM with an ODM.
3. Incorporating some of the short-term dynamic features of power systems directly into an LTPM in the form of additional constraints that aim at simulating some of the power system's technical requirements.

Note that another relevant issue regarding VRE integration in power systems is beyond the scope of this study, i.e. because VREs rely on dispersed resources, their penetration would certainly require a deep transformation of the grid's topology structure. Several studies have dealt with this issue, which remains an active field of research (for example Shawhan et al. for the Eastern part of the US [8], Hagspiel et al. for Europe [9], Pesch et al. for Germany [10], Zhang et al. for China [11]).

In what follows we focus only on LTPM-based studies since they perform an investment analysis over the whole period studied. Other studies, relying on ODM only or other tools, are well suited for answering some issues concerning the impacts of high shares of VREs, for instance the amount of storage and balancing required to prevent VRE curtailment [12], but they miss the assessment of long-term investment decisions. Therefore, they are not relevant for our investigation.

In order to deal with the first approach presented above, based on LTPMs only, Park et al. explored the optimal power mix in South Korea relying on different proportions of renewables using a TIMES model with a detailed assessment of renewables supply curves. Their study indicates a high share of solar photovoltaic (PV), from 25% to 40%, in 2050 depending on the overall penetration of renewables in power production and the comparative evolution of supply costs. However, the authors do not clearly state how they dealt with intermittency issues [13]. Kannan et al. tested the benefits of increasing the temporal details of a TIMES model (STEM-E which describes the Swiss power sector) comparing an 8 time-slice (TS) model and the same model with 288 TSs. They showed that the model with fewer TSs tended to overestimate baseload capacities compared to the model with more TSs [14]. Nelson et al. conducted an analysis of low carbon scenarios for the Western North American power system (WECC) until 2030 using the SWITCH model. This model features a high level of spatial details with 50 interconnected load areas as well as a fairly accurate temporal description with 144 TSs and post-optimization hourly dispatch verification. Depending on the assumptions, a 54% carbon emissions reduction target in 2030 compared to 1990 levels would lead to between 17% and 29% of power supply from VREs. In all of the simulated periods and for all scenarios, the dispatch verification did not find a single hour during which production could not meet demand, showing that their LTPM is quite robust for power system sizing purposes, at least for intermediate penetration levels of VREs [15]. Blanford et al. conducted a deep analysis of Clean Energy Standards in the US using the REGEN[1] model and dividing the US into 15 regions. They used an algorithm to choose the 84 TSs of their model in a way that maximizes the capture of residual load[2] variability. One of their results is the high need for backup capacity in the scenarios with the highest penetration of renewables, which can be reduced if grid extensions are available [16]. Ludig et al. assessed under what conditions of technology availability (carbon capture and storage and offshore wind) and demand evolution the German power system could reach the government's targets by 2050.[3] For this purpose they used the LIME-D model, which represents the German power system divided into 5 regions, based on 48 TSs. The TSs were built to depict the seasonal and intraday variability of demand but also different typical days of wind power production (one day with a low wind resource, one with medium wind resource and one with high wind resource). Thanks to this TS choice, instead of a very poor description of wind variability (only 10% of this variability), they were able to obtain a much more satisfying description (65% captured). On top of this representation of wind variability, the model includes an additional TS schematizing extreme-peak demand as well as minimum backup capacity constraints. This temporal representation allows for better assessment of power system sizing. Within this framework, authors obtained similar results as in [16] concerning the trade-off between the different mitigation technologies (wind power, nuclear power, CCS and grid-extensions) [17]. A similar study was conducted by Schmid et al. for the European and MENA[4] power system with the LIMES-EU model [18]. Pfenninger et al. assessed several decarbonisation scenarios for the United Kingdom (UK) electricity sector until 2050 using the Calliope model with 550 time-slices (TS) each represented year. In their model, the UK was divided into 20 regions and the grid

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[1] One of the main features of this model is the soft-linking between an LTPM with a computable general equilibrium model. The macroeconomic aspects of renewables penetration are beyond the scope of our study and so we focus here on the LTPM-part of the REGEN model.

[2] The residual load is calculated as the overall load minus the production from all VRE sources.

[3] 98% of GHG emissions reductions compared to 1990 levels and 80% RES penetration together with nuclear phase-out by 2022.

[4] Middle East and North Africa.