Energy Policy 95 (2016) 135–146

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Nuclear and intermittent renewables: Two compatible supply options? The case of the French power mix

Camille Cany[a,b,*], Christine Mansilla[a], Pascal da Costa[b], Gilles Mathonnière[a], Thierry Duquesnoy[a], Anne Baschwitz[a]

[a] I-tésé, CEA, Université Paris Saclay, F-91191 Gif-sur-Yvette, France
[b] Laboratoire Genie Industriel, CentraleSupélec, Université Paris-Saclay, Grande Voie des Vignes, 92290 Chatenay-Malabry, France

HIGHLIGHTS

- Nuclear flexibility is examined to balance the system with high renewables share.
- Impacts of wind and solar shares on the nuclear load factor and LCOE are assessed.
- Nuclear fleet replacement must be progressive to ensure competitive load-following.
- Incentives are needed for nuclear to compete with CCGT gas back-up.
- We recommend considering nuclear flexibility through the power use.

ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form
20 April 2016
Accepted 24 April 2016

Keywords:
Nuclear power flexibility
Intermittent renewable energy sources
Power system economics
Back-up
Low-carbon source synergy

ABSTRACT

The complementary features of low-carbon power sources are a central issue in designing energy transition policies. The French current electricity mix is characterised by a high share of nuclear power which equalled 76% of the total electric production in 2015. With the increase in intermittent renewable sources, nuclear flexibility is examined as part of the solution to balance electricity supply and demand. Our proposed methodology involves designing scenarios with nuclear and intermittent renewable penetration levels, and developing residual load duration curves in each case. The load modulation impact on the nuclear production cost is estimated.

This article shows to which extent the nuclear annual energy production will decrease with high shares of intermittent renewables (down to load factors of 40% for proactive assumptions). However, the production cost increase could be compensated by progressively replacing the plants. Moreover, incentives are necessary if nuclear is to compete with combined-cycle gas turbines as its alternative back-up option.

In order to reconcile the social planner with plant operator goals, the solution could be to find new outlets rather than reducing nuclear load factors. Nuclear flexibility could then be considered in terms of using its power to produce heat or hydrogen.

1. Introduction

1.1. Background

The current international context is characterised by emerging intentions to switch to low-carbon energy mixes, with country-specific energy transition pathways. The production of heat and electricity is the first contributor to greenhouse gases worldwide as it emitted a quarter of the total emissions in 2010 (French Ministry for the Environment, Sustainable Development and Energy, 2015). Thus electricity production appears to be a key parameter in working towards lower carbon contents. As stated in the SET Plan Integrated Roadmap of the European Commission: "*The decarbonisation of electricity production is the centre-piece of the Energy Roadmap 2050. All scenarios studied in the Roadmap show that electricity will have to play a much greater role than now*" (European Commission, 2014a). The electric power mix is a core issue of the energy transition: significant decarbonisation of the energy system will involve both decarbonising the power sector and enhancing the role of electricity, particularly through sector coupling, like power-to-heat and power-to-mobility, either

* Corresponding author at: I-tésé, CEA, Université Paris Saclay, F-91191 Gif-sur-Yvette, France.
E-mail address: camille.cany@cea.fr (C. Cany).

http://dx.doi.org/10.1016/j.enpol.2016.04.037
0301-4215/

directly with electricity, or synthetic gas as final energy.

To promote decarbonisation of the power system, the general 3×20 European directive proposes renewable penetration goals (European Union, 2009). The recent European agreement appears proactive; by announcing a binding target of at least 27% of renewable energy on a European level by 2030, it will promote such decarbonisation practices (European Commission, 2014b). In France, 27% of the electricity is to be produced by renewable resources by 2020 (European Union, 2009), and this share will increase to 2050. In 2015, the share of renewable power already reached 19% of the domestic production, namely approximately 100 TWh (RTE, 2015a). The major fraction of growth will come from intermittent renewable power plants, which challenges the possibility of maintaining the reliability target level of the power system (Gross et al., 2006); (Hart et al., 2012). Among renewables, wind and solar are expected to contribute about 10% to the French electricity production in 2020 (ANCRE, 2013); (RTE, 2015a), and according to some scenarios, they could contribute more than 50% to the total electricity production by 2050 (ADEME, 2013).

1.2. The impact of intermittent sources on power systems

To ensure the reliability target level of a power system, some power plants have to certify that they are available to supply power when the power deviates from the expected value. This is what is commonly called 'back-up power'. The addition of intermittent renewable power plants in a power system triggers new needs for back-up power to provide the system with additional flexibility. This is true both in the short term (i.e. the operational back-up meets balancing requirements) and in the long term (i.e. the capacity back-up meets adequacy requirements) (Luickx et al., 2008). Ma et al. (2013) defines the term flexibility as "the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at reasonable cost, over different time horizons".

Intermittent renewable power plants are characterised by power variability, some uncertainty and non-dispatchability, not to mention a current priority dispatch. In any case, their low variable costs place them first in the merit order. In the last few years, the findings first led to defining and quantifying the specificities of intermittent system-dependent production profiles (Hart et al., 2012; Keppler and Cometto, 2012; Luickx et al., 2008; Perez-Arriaga and Batlle, 2012; Ruiz Gomez, 2012; Wagner, 2012; Wan, 2011). They identified average load factors, attempted to quantify additional high power ramps and amplitudes induced for the residual load pattern, and examined the issue of power surplus.

Most power system studies analyse the impact of intermittent renewable power plants on the power system, and the related needs for more operational and capacity back-up. In particular, the capacity credit of the intermittent sources added to the system must be assessed in order to quantify the need for capacity back-up. Both back-up needs depend on key parameters pointed out by findings shared by (Davis et al., 2013; Doherty et al., 2006; Gross et al., 2006; Hand et al., 2012; Hoogwijk et al., 2007; Keane et al., 2011; Perez-Arriaga and Batlle, 2012). On the one hand, these parameters are inherent to a power system (i.e. relative to the reliability target level, to the features of the power system before introducing intermittent sources and to the features of the intermittent fleet added to the system). On the other hand, they are highly linked to approximations used to evaluate these needs. According to Keane et al. (2011), calculations must rely on time series of data for the electric demand that must coincide with the production of intermittent renewable sources, covering at least several years with an hourly time frame, along with a complete inventory of dispatchable sources, associated default rates and maintenance schedules.

The whole cost associated with intermittent renewable penetration should be considered in light of their specificities. Costs related to intermittency are highly sensitive to these parameters, so their quantification should be interpreted with caution, which is all the more complex as different terminologies are used from one country to another. These costs are the result of low capacity credits of intermittent sources. Authors (Connolly et al., 2010a; Gross et al., 2006; Keppler and Cometto, 2012; Perez-Arriaga and Batlle, 2012; Skea et al., 2008) agree on the three components which define these costs:

- Balancing costs that include the change of load factors for installed capacities. They result from new operational needs linked to variability and uncertainty of these sources
- Adequacy costs that are closely related to the assumed capacity factor of the power plants. They result from new needs for capacity back-up
- Grid costs that result from new needs for network reinforcement.

Ueckerdt et al. (2013) propose to include all these cost components in the concept of 'system LCOE'[1] to make it possible to perform a thorough comparison of technologies.

1.3. French case and the issue of nuclear flexibility

The French case is very specific. The French power system is currently characterised by a high nuclear penetration: the nuclear fleet supplied 82% of the French domestic consumption and 76% of the total demand (including exportations) in 2015 (RTE, 2015b). Nuclear power will remain a significant contributor to the French power system in the medium term, as a low-carbon power source. The nuclear share is to be reduced to 50% of the power production from 2025 onwards, and the renewable share should reach 40% by 2030 (French Government, 2015). Furthermore, the choice of the nuclear fleet replacement policy is at the core of the French power debate as half of the fleet will be older than 40 years by 2025 (Cour des comptes, 2014).

The energy transition in the French context needs to be pursued by taking into account available technologies and by implementing potential synergies to drive low-carbon power sources with complementary features. With high intermittent renewable penetration, all back-up technologies should be considered, given their characteristics. Besides peaking unit production (e.g. gas turbines), options such as storage, demand (or supply) curtailment, interconnections and even baseload power modulation should be examined as part of the solution (Hand et al., 2012).

The nuclear abilities to modulate power are defined on the scales of a fleet and of a reactor. On a fleet-scale, limitations are related to the dynamics of the fleet in operation with organisational, economic and administrative constraints. Increasing the fleet's participation in load-following entails additional operating costs linked to a higher forced loss rate and higher maintenance needs. While additional operating costs are hard to quantify in advance, they are minor compared with costs linked to the nuclear load factor reductions due to load-following (Bruynooghe et al., 2010; EDF, 2013).

On a reactor-scale, nuclear reactor flexibility is limited by intrinsic physical properties linked to the crucial need to maintain the integrity of the first barrier (for instance, avoiding cladding-pellet interactions) and to minimise effluent releases related to the use of boron in the core. These properties limit the maximum allowable power ramp (around 5% of nominal power (Pn) per

[1] The system levelised cost of electricity.