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Load-following with nuclear power: Market effects and welfare implications

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ABSTRACT

This paper analyses the economic factors that drive nuclear power load-following in future European electricity systems. A power plant dispatching model is built to simulate deregulated markets, in order to identify to what extent additional flexibility is needed from nuclear power due to more renewables. We contribute to the literature with an economic perspective of the nuclear load-following by means of numerical simulations of several European power systems that will pursue the nuclear policy in 2050. Results show that intermittency would make flexible nuclear reactors cycling more often and retire earlier. The highest requirements for flexibility would be in systems with high shares of nuclear, renewables or coal-fired plants (Central-Western Europe and certain Central-Eastern European countries) and in systems with low grid interconnections (Western Europe and South-West). Load-following implies lower capacity factors for nuclear plants, except for Central-Western Europe where operating flexibly would allow reactors to supply more output than in steady-state mode. The lowest generation cost is found in Nordic countries where most of the flexibility is provided by hydro-units, and hence nuclear power plants operate mostly baseload. Ensuring flexibility becomes financially interesting when nuclear power plants are not the marginal technology setting the clearing price; in this way the infra-marginal rent allows operators to capture high revenues. It is shown that nuclear flexibility is profitable from a broader social welfare perspective, such as safe baseload units' operation, renewables' integration, system operators' balancing, and consumer's price.

1. Introduction

The European Energy Roadmap to 2050 frames the energy transition by setting out four routes to decarbonisation, such as energy efficiency, renewables, nuclear energy and carbon capture and storage (EC, 2011). The decarbonisation objective involves high rates of renewables, e.g. between 55% and 97% in the final power demand by 2050, along with a significant contribution from nuclear energy in those countries where a pro nuclear policy is pursued. The interaction between intermittent renewables and the conventional technology mix is a matter of concern for policy makers for both short-run dispatching of generators and long-run investment planning in new power plants.

This research evaluates the requirements for nuclear flexibility and the cost-benefit aspects in various power systems in European Union (EU). Countries have been selected due the variety of drivers influencing the operation of nuclear power plants (NPP), such as different renewables levels, generation technology mix and grid interconnection with the neighbouring markets.

The literature is rich in papers dedicated to the flexibility of power plants and their ability to follow the load. Firstly, cycling comes with costs. Kumar et al. (2012) estimate that from cold to warm and hot start, load-following costs in the United States are in the range of 0.6–1.9$/MW for gas-fired units and of 2.0–3.4$/MW for coal-fired units. Troy et al. (2010) show that the number of start-ups of thermal units in the Irish power system increases with the wind energy share; yet at higher than 30% wind rates, the start-ups for coal units decrease with raising primary reserve supply. Flexible NPPs operating load-following will bear additional costs with the retrofit and design conversion, O&M costs due to the wear of components, some fuel costs, staff costs and intensified safety measures (IAEA, 2018).

Secondly, load-following compresses load factors of conventional generators, down to 62% for nuclear power plants and to 7% for gas-fired units in Europe, which could reduce the financial incentives to invest in baseload and peak capacities (Ketterer, 2014; Wurzburg et al., 2013; Bertsch et al., 2016). The compression effect could be even stronger, e.g. 40%, if nuclear was to substitute all flexible technologies and imports (Cany et al., 2016). Currently, the loss due to the load-following is estimated at 135,000–250,000 €/day for a nuclear plant of

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1,400 MW operating in Europe (OECD-NEA, 2012a). It is shown that a viable model of baseload operation in front of renewables is possible only if nuclear plants co-generate power and heat as well, e.g. for district heating, desalination and hydrogen production (Locatelli et al., 2017), or for biomass conversion into liquid transport fuels (Forsberg, 2009).

From a system perspective, nuclear load-following can maximise the social welfare, as shown in Lykidi and Gourdel (2015) by means of an optimisation model with monthly time-steps. These aggregated models often ignore significant ramping ups and downs and the daily and hourly pressure put on reactors. Instead, highly detailed time-resolution models are needed to accurately test the ramping requirements (Komiyama and Fujii, 2015). The need for nuclear power generation to be more flexible with faster ramping rates is one of the important factors in determining the design of the future nuclear reactors, such as to follow the development of energy markets (Magwood and Paillere, 2018; Nourbakhsh et al., 2018).

This research builds tools to simulate future power markets and the cycling needs from NPPs. For potential excessive cycling, we use cost estimates of reactors' upgrading and assess the potential benefits from operating load-following. We next define the capability of NPP to operate flexibly. Then we describe the methodology based on power plant dispatching. Numerical findings will depict the value of the nuclear flexibility provision and the key drivers of nuclear power economics in the future.

2. Nuclear capability to provide flexibility

By definition, load-following represents the change in the generation of electricity to match the expected electricity demand as closely as possible (IAEA, 2018). In practice, countries with large nuclear power shares (France) and high intermittent renewables (Germany), need NPPs to operate load-following. In other systems, load-following is currently not licensed (Spain) or needs approval from system operators and nuclear national safety authorities (USA; EPRI, 2014).

Load-following is measured by the transient from full power to minimum load and back to full power. Technically, the modern light water nuclear reactors can operate flexibly once or twice per day in the range of 100% to 50%–25% of the rated power, with a ramp rate of up to 5% of rated power per minute (OECD-NEA, 2011). The number of cycles is limited to 2 operations per day, 5 per week, cumulatively 200 per year (EUR, 2012). In practice, two situations occur: frequent load-following over a small range of the rated thermal power, the so-called light cycles; and less frequent cycling but over a large range of the rated power, or deep cycles (IAEA, 2018). The amplitude is in the range of 100%–60% of the nominal power for light cycles, and between 100% and 25% for deep cycles (AREVA, 2009; EDF, 2013). Fig. 1 represents cycles with different durations and amplitudes, distinguishing short from long cycles and deep from light cycles.

Ludwig et al. (2010) analyse the licence of a German Pressurized Water Reactor (PWR) and define the transient budget of cycles, as being the number of cycles with bounded amplitude allowed over the plant lifetime.

Table Reading. A PWR reactor could perform 100,000 cycles of 10% of the rated power amplitude over the plant lifetime (a 10% depth cycle goes from 100% of the rated power to 90% and back to 100%). The reactor can also perform 100,000 cycles of 20% depth, 15,000 cycles of 40% depth and 12,000 cycles of 60% depth.

Load-following allowed by the licence of a flexible reactor (Table 1) is provided for in a planned manner,[1] and this enhances no additional cost. By contrast, unplanned cycling would account for more fuel costs due to a reduced usage of uranium during one refuelling cycle, e.g. in the range of 17–34% of the initial fuel cost (Persson et al., 2012). Planning load-following requires a good management of the NPP fuel, such as to anticipate the usage rate of the uranium at the beginning of the cycle (IAEA, 2018). However, neither practice nor literature could defend a robust cost estimate of cycling based on the speed and the frequency of generator ramping up and down. Next the effective operation of NPPs in terms of cycling is compared with the licensed transient budget in order to identify cases with additional reactor fatigue requiring upgrading.

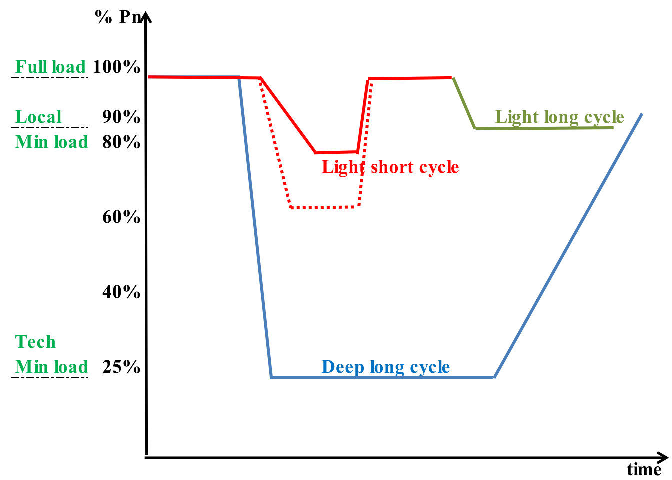

Fig. 1. Load-following capability of a PWR by cycle type.

Table 1
The design of PWR Konvoi reactor.
Sources: Ludwig et al. (2010).

Load cycle (% rated thermal power)	Number of load cycles
100-90-100	100,000
100-80-100	100,000
100-60-100	15,000
100-40-100	12,000

3. Methodology. Model. Scenarios

3.1. Methodology

Assumptions. A power plant dispatching model is built to simulate major technology types in the European power systems and to ensure the hourly equilibrium supply-demand (Fig. 2). The study case covers deregulated power markets, which implies that power plants are called as a function of their position in the merit order curve.[2] The study case selects deregulated markets where the nuclear plants are paid at the spot market price. Regulated markets instead would apply a full-cost recovery policy, based on nuclear levelised cost of electricity.

The model simulates the base year 2012 and the projection year 2050 in those countries with future nuclear power projects. The EU-28 Member States are grouped into five market regions. By 2050, thirteen countries plan to pursue using nuclear energy, according to the EU Reference Scenario EC (2013).[3] By region, these countries are as

[1] *Planned* load-following refers to changes in the electrical output and associated thermal power which are planned weeks or days in advance. *Unplanned* changes occur within a few minutes of a request from the grid system operator, and achieves a significant change in output within 10–20 min (IAEA, 2018).

[2] Merit order curve is the electricity supply curve built by ranking the power generators by ascending order of their short-run marginal cost of production. Power plants are dispatched together with the amount of energy to be generated, from low merit-order baseload units to high merit-order peak-load units.

[3] An update of this scenario (EC, 2016) presents different trends of the nuclear capacities in Europe by 2050, e.g. one third lower. We simulate however