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Optimal management of flexible nuclear power plants in a decarbonising competitive electricity market: The French case

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ABSTRACT

The road towards the decarbonization of electricity leads to high deployment of low-carbon power sources including intermittent energy sources. In this context, flexible nuclear power plants could play a significant role because they do not produce CO_2 emissions and under certain conditions flexible operation is necessary to ensure the stability of the electricity grid. Flexible nuclear reactors have the ability to load-follow the predicted fluctuations in demand. However, high fixed costs of nuclear production, tighter regulations since the Fukushima accident and the extensive participation of renewable sources in the energy mix challenge the economic profitability of nuclear production. Consequently, a question that arises is how nuclear power producers can manage flexible nuclear production in order to maximize their profits. We proved that optimal production behaviour is not characterized by constant nuclear production unless further investments in thermal capacity are realized. On the contrary, both nuclear and thermal production are flexible at the optimum level.

1. Introduction

Several reasons explain why nuclear power does not serve only as a baseload[1] power generation technology but it has to be flexible in order to participate significantly in the modulation of supply between winter (season of high demand) and summer (season of low demand) in order to ensure the stability of the electricity grid [1,2]. Some of the reasons are presented below [3,4]; they are analytically described in our previous work [35]: (i) high percentage of nuclear generation capacity; (ii) growth in renewable or non-dispatchable production. If there is an important share of intermittent[2] and nuclear power sources on the same electricity grid, the nuclear power plants must be capable of operating in load following mode to balance the fluctuations of total power generation; (iii) large nuclear power generating units in a small electrical system; (iv) transmission system constraints since the capacity of the transmission network to which the NPP is connected may be limited; (v) constraints on non-nuclear (thermal) generating units because of increasingly strict environmental legislation; (vi) changes in electricity market rules. Technically, nuclear reactors of modern design[3] are capable of flexible operation [1,7]. In flexible operation, the amount of electricity supplied by a generating system at any given time (load) follows the predicted evolution of

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[1] Baseload plants are the production facilities used to meet some or all of a given region's continuous electricity demand, and produce electricity at a constant rate, usually at a low cost relative to other production facilities available to the system.

[2] An intermittent energy source is any source of energy that is not continuously available due to some factor outside direct control. The intermittent source may be quite predictable, for example, tidal power, but cannot be dispatched to meet the demand of a power system.

[3] The pressurized water reactor (PWR) and its evolution, the new european pressurized reactor (EPR), are examples of third and III+ generation nuclear reactors which are designed to accommodate load-following operation [5,6].

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energy demand (daily and seasonal) [1–3]. In fact, this flexibility is primarily due to the new types of fuels which affect the constraints that determine the speed of increase and decrease of production. This type of constraint (called ramping rate constraints) binds the change of operation level of a unit between two successive periods. In principle, all nuclear reactors might reasonably be regarded as having some capacity to follow load. In practice, however, the ability to meet grid needs efficiently and safely is restricted to a certain set of design types (for technical engineering, safety and licensing reasons).

However, despite the potential advantages of nuclear energy (because of its low variable costs and zero CO_2 emissions) including the flexibility of nuclear reactors, nuclear power is considered an expensive technological option for generating electricity [3,4], [8–11]. This is due to various economical reasons such as the high fixed costs of nuclear involved in the conception and the construction of a nuclear unit, the decommissioning[4] of the unit at the end of its life, insurance costs as well as costs incurred in order to obtain regulatory approvals for the construction and operation of the units especially after the Fukushima accident in 2011 and expenses arising from uncertainties related to the construction schedule (e.g. the nuclear power plant of Flamanville, of Olkiluoto). Moreover, we need to consider the costs of renovation that may arise during the economic life of a nuclear power plant (e.g. renovation for the maintenance of aging plants, the extension of the lifetime of existing nuclear plants, the extension of the production capacity, the improvement of production performance, the improvement of nuclear safety, the increase of economic viability of facilities, etc.). Another reason is that high levels of renewable output have significant effects on the level and pattern of wholesale prices. Wind and PV generators have marginal costs of practically zero, and thus displace fossil-fuel generators with higher marginal costs, which inevitably reduces wholesale prices. This effect will be exacerbated, at least in the short term, if the entry of renewable capacity is not matched by the exit of other plants. An industry with excess capacity will see lower average prices which can make it difficult for nuclear operators to amortize their fixed costs. Germany is a typical example of a country which decided to shut down all its nuclear units after the Fukushima nuclear accident and introduce a large amount of renewable energy within its national energy mix. German wholesale electricity prices have fluctuated substantially with the cost of imported natural gas, but the link between wholesale electricity and natural gas prices breaks down after 2011 when the amount of solar energy increased significantly. In 2014, almost 28% of German electricity came from renewables while nuclear provided 16% of electricity production. Italy constitutes a similar example since rapid growth in the deployment of solar, wind and bio energy in recent years lead to Italy producing over 40% of its electricity from renewable sources and there are no plans for new nuclear reactors. Other countries however, such as the U.K.,China, South Korea and India are pursuing ambitious expansion plans for their nuclear power capacity and many others are giving "serious consideration" to introducing nuclear power into their energy mix (e.g. the United Arab Emirates, Turkey, Belarus). Thus, globally, a question that may arise is how to manage flexible nuclear power plants in order to maximize producers' profit.

[4] Nuclear decommissioning is the dismantling of a nuclear power plant and decontamination of the site to a state no longer requiring protection from radiation for the general public. The main difference from the dismantling of other power plants is the presence of radioactive material that requires special precautions. This is also why the decommissioning cost is more important for nuclear than for other technologies (e. g. coal, gas).

In France, the nuclear fleet adjusts its production in order to (partially) follow the variations of energy demand. This is mainly due to the significant share of nuclear power generation (75% of electricity) in the national electricity mix. An illustration of the operation of the French nuclear power plants is provided by the monitoring report of the French energy regulator (CRE) realized in 2007 [12]. Nevertheless, the Energy Transition law for the first time limits the share of nuclear in the power generation mix for France in favor of the development of renewable energy sources. The nuclear share must be reduced from the current 75% of electricity generation to 50% by 2025 and it caps nuclear electricity capacity at its current level (63 GW) while the share of renewables is estimated at 23% by 2020. At the same time, the French nuclear operator (EDF) invests nearly 51 billion (estimated cost for the period 2014–2025) to extend all 58 reactor lifetimes[5] until the age of 60 years. Therefore, we conclude that France is a typical nuclear-reliant country that operates its nuclear power plants flexibly; further the tighter regulations after the Fukushima accident, the increasing costs to maintain aging plants, the lifetime extension of the French nuclear reactors as well as the need to develop its own renewable energy industry make it a particularly interesting case study for our main question. Additionally for France we have access to analytical operational data necessary for our modelling [5,10], [18–20], [30–32].

A key point of our research consists of the characteristic of the "reservoir" of nuclear fuel which results from the discontinuous reloading of nuclear reactors. Every 12 or 18 months, nuclear reactors reload their fuel and then a period of production named "campaign" begins. Its length is determined by the maximum number of days during which a nuclear unit produces until exhaustion of its fuel load. In a market based electricity industry, the objective should be the maximization of the value of electricity production. In the medium-term, a producer sets its production level during a campaign of nuclear fuel reservoir to respond to the seasonal variations of demand and to maximize its profit. Consequently, the question of optimal management of the nuclear fuel reservoir during a campaign of production arises. The novel characteristic of the nuclear fuel reservoir has been initially presented in Ref. [35] where we analyzed its optimal management from the point of view of social welfare under a number of technical-economical constraints regarding nuclear production. These constraints need also to be considered in our present work where we look at the maximization of the inter-temporal profit of producers. This makes our model instantly complex. Firstly, we look at the constraints imposed by the flexible management of nuclear units (minimum/maximum production constraints). Generally, a nuclear unit can vary its capacity level between the nominal capacity and the technical minimum. A nuclear unit can vary its capacity level between the nominal capacity and the technical minimum. The minimum requirements for the maneuverability of modern reactors are defined by the utilities requirements that are based on the requirements of the grid operators. For example, according to the current version of the European Utilities Requirements (EUR) nuclear power plants must at least be capable of daily load cycling operation between 50% and 100% of its nominal capacity. Most of the modern designs implement even higher maneuverability, with the possibility of planned or unplanned load-following. Today, some reactors in France operate in the load-following mode with large daily power variations of about 50% of nominal capacity [3]. An EPR reactor can maneuver between 25% of nominal capacity and 100% of nominal capacity in order to follow-up load. We take into

[5] Thirty years is the average age of the French nuclear fleet. Twenty of 58 reactors currently are 35 years old or more.