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Review

Cogeneration: An option to facilitate load following in Small Modular Reactors

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A B S T R A C T

Nuclear Power Plants (NPPs) have been historically deployed to cover the base-load of the electricity demand. Nowadays some NPPs might perform daily load cycling operation (i.e. load following) between 50% and 100% of their rated power. With respect to the insertion of control rods or comparable action to reduce the nuclear power generation, a more efficient alternative might be the "Load Following by Cogeneration", i.e. diverting the excess of power, respect to the electricity demand, to an auxiliary system. A suitable cogeneration system needs:

1. To have a demand of electricity and/or heat in the region of 500 MWe–1.5 GWt;
2. To meet a significant market demand;
3. To have access to adequate input to process;
4. To be flexible: cogeneration might operate at full load during the night when the request of electricity is low, and be turned off during the daytime.

From the economic standpoint, it is essential that the investment in the auxiliary system is profitable. This paper provides a techno-economic assessment of systems potentially suitable for coupling with a NPP for load following. The results show that district heating, desalination and hydrogen might be technically and economically feasible.

1. Introduction

The increasing penetration of variable renewable energy and Nuclear Power Plants (NPPs) in several developed and developing countries is forcing NPPs to follow the energy demand i.e. to operate at variable power output (NEA - OECD, 2011). As a consequence, NPPs vendors and utilities have studied the capability of the plants to work in the so-called 'Load Following' (LF) mode by temporarily reducing the power output and consequently the overall electric energy produced. As explained later, reducing the power in the primary circuit is not ideal, while the cogeneration, in some scenarios, might be more economically convenient. The goals of this papers are: to analyse the requirements of cogeneration options for LF with NPPs; to review of the most significant results in this field; to point out the most interesting systems for future studies.

1.1. *The need of load following with Nuclear Power Plants*

Historically, NPPs have been mainly seen as a baseload source of electrical energy. This is the most economical and technically straightforward mode of operation: power changes are limited to frequency regulation for grid stability purposes and shutdowns for safety purposes. Still nowadays, the majority of NPPs are used for the baseload and operate at a fixed power level. However there is an increasing number of countries such as France and Germany, where this situation has changed, and NPPs are forced to work in the LF mode (NEA - OECD, 2011). For instance, in France, the share of nuclear power in the national electric portfolio is so relevant (about 75%), that particularly during the night-time there is a surplus of production (WNA, 2016).

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Although France is an exception several countries that present shares above 50% (Belgium, Hungary, Slovakia and Ukraine) face similar problems (NEI, 2016). Furthermore, even in countries not having a very high penetration of nuclear power (e.g. South Korea), the LF can be imposed in specific regions with several NPPs. NPPs would also be required to LF when a large proportion of power portfolio is constituted by large-scale deployment of intermittent sources of energy like photovoltaic or wind (e.g. in Germany) (NEA - OECD, 2011). Since most of the renewable power plants (i.e. wind farms) are not dispatchable, other plants have to reduce their power level to avoid an excess of supply compared to the electric power demand (NEA - OECD, 2011). This situation is forcing the utilities to implement or improve the flexibility of their NPPs and to adapt the electricity supply to daily or seasonal variations of the power demand i.e. to do the LF.

The requirements for a NPP to perform LF are specified in (NEA - OECD, 2011) and mainly consist in:

- The capability to operate between 50% and 100% of the nominal reactor power;
- The output variation rate, at least, equal to 3% of nominal power per minute;
- The capability to perform at least the following number of load variation: two per day, 5 per week, 200 per year.

Modern NPPs, like the PWRs operating in France, are designed to have a large manoeuvring capability: for instance, the European Pressurised Reactor (EPR) can perform LF between 25% and 100% of nominal power (P_N), and supports power variation speeds up to 5% P_N per minute (UK-EPR, 2012). Several French NPPs follow a variable load program, with one or two large power changes per day. This can be made in different ways, mainly:

- For PWRs: by inserting the control rods (made of neutron absorbers);
- For BWRs: by changing the coolant flow rate (by mean of recirculation pumps), or with the control rods.

All these methods induce a decrease of the reactivity into the core, i.e. a variation of the thermonuclear power production. This introduces thermomechanical stresses in the reactor fuel and components. Even though this problem can be mitigated by modern NPPs designs (NEA - OECD, 2011), the NPP still essentially remains under-utilized, since a reduction of the production represents a loss of revenues without any significant variable cost reduction. Indeed, differently from gas power plants, there is no relevant cost saving in decreasing the electricity production, because:

- Capital cost is a sunk fixed cost;
- O&M costs (e.g. staff) are fixed costs, and independent from the power rate;
- Nuclear fuel accounts only for about 10%–15% of generation costs and there is a non-linear relationship between power produced and "fuel usage".

Thus, the economic consequences of LF are mainly related to a reduction in revenue with substantially unvaried costs. This causes an increase in capital costs incidence on the unit power output.

1.2. The key idea: load following by cogeneration

The key idea of the 'LF by Cogeneration' is to meet electricity market requirements and avoid an economic penalty at the same time. This is achieved by operating the NPP at its nominal power all the time, leaving the primary circuit conditions unchanged. During the high load/high price hours (day) the nuclear power is fully converted into electricity to the grid, while during hours of low demand/low price (night) the excess power can be directed to an external system (e.g. a desalination plant) producing valuable by-products (e.g. fresh water). The coupling is particularly virtuous for those systems that require large amounts of energy in terms of heat or electricity and whose main cost of production is represented by the energy supply. Cogeneration based on heat supply is preferable since the heat-to-electricity conversion is avoided with related efficiency losses. Small Modular Reactors (SMRs) are ideal for this kind of application (Locatelli et al., 2015) as discussed also in sections 2.1.

Reasonably, it should be distinguished between pre-programmed LF and dynamic LF. In case of pre-programmed LF, utilities know the amount of electricity to produce each hour. This information come from historical data about electricity consumption during the nights or the week-ends and are reflected in the "day-ahed electricity market" or comparable mechanisms. Alternatively NPP dynamically LF or adjust its power output according to the change of power produced by not dispachable renewables, e.g. wind farms. The application of cogeneration with dynamically LF is more challenging than the programmed LF (generally applied in all NPPs). This paper investigates pre-programmed LF, while dynamic LF is an enviseged future development.

2. Methodological consideration

2.1. Criteria for selecting the nuclear power plant

2.1.1. Introduction to small modular reactors

NPPs can have different sizes. Small sized reactors are defined as those with electric power inferior to 300 MWe while medium-sized reactors are those with electric power in the range 300–700 MWe (IAEA, 2007b). More recently the IAEA defined small modular reactors (SMR) *"as advanced reactors that produce electric power up to 300 MW(e), designed to be built in factories and shipped to utilities for installation as demand arises."* (IAEA, 2016). Several SMRs design, detailed in (IAEA, 2014) and (IAEA, 2016), are currently at different stages of development around the globe. Considering SMRs (Ingersoll, 2009) provides a good summary of their innovative features; *"reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics"*.

Several papers discuss how SMR can be economically competitive with Large Reactors (LR), in certain scenarios and contexts. In particular, SMR might balance the "diseconomy of scale" with the "economy of multiples". (Carelli et al., 2007) analyse specific factors, such as grid characteristics, construction time, financial exposure, modularization, learning, which distinguish SMR from LR in the evaluation of the capital cost. When these factors are taken into account, the capital cost might not be a discriminant between the two technologies. (Boarin et al., 2012) provide a full economic analysis reaching the same conclusions for a large plant vs. SMR plant comparison; (Locatelli and Mancini, 2011a) offer a portfolio level analysis of large versus SMR plants. (Locatelli and Mancini, 2011b) discuss the effects of "non-financial parameters," such as electric grid vulnerability, public acceptance, the risk associated with the project, on the evaluation of the best reactor size for investment in the nuclear sector. For many of these parameters, the authors show many benefits of SMR respect to LR. One of the key SMR advantages is the possibility to turn a large investment into a scalar and modular one. The construction of a single large reactor of GWe scale is a very risky single investment