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Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis

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ABSTRACT

Load following is the possibility for a power plant to adjust its power output according to the demand and electricity price fluctuation throughout the day. In nuclear power plants, the adjustment is usually done by inserting control rods into the reactor pressure vessel. This operation is inherently inefficient as nuclear power cost structure is composed almost entirely of sunk or fixed costs; therefore, lowering the power output, does not significantly reduce operating expenses and the plant is thermo-mechanical stressed. A more attractive option is to maintain the primary circuit at full power and use the excess power for cogeneration. This paper aims to present the techno-economic feasibility of nuclear power plants load following by cogenerating hydrogen. The paper assesses Small Modular nuclear Reactors (SMRs) coupled with: alkaline water electrolysis, high-temperature steam electrolysis, sulphur-iodine cycle. The analysis shows that in the medium term hydrogen from alkaline water electrolysis can be produced at competitive prices. High-temperature steam electrolysis and even more the sulphur-iodine cycle proved to be attractive because of their capability to produce hydrogen with higher efficiency. However, the coupling of SMRs and hydrogen facilities working at high temperature (about 800 °C) still requires substantial R&D to reach commercialisation.

1. Introduction

1.1. *The need for load following*

The global demand for energy will increase by 48% from 2012 to 2040 primarily due to non-OECD countries [1]. The journey towards sustainable energy production, therefore, faces several challenges, requiring the contribution of different technologies to achieve this long-term goal. Nuclear Power Plants (NPPs) can be deployed along with renewable power plants to achieve the long-term perspective of sustainable development [2,3].

Due to the predominance of fixed costs, NPPs are considered a base load power technology [4]. NPPs have a lower marginal production cost than gas or coal. Since the demand for electricity changes continuously during a single day, the adjustment on the offer-side is usually obtained by manoeuvring gas or coal power plants. This is done since the 70s and it is still mostly the case nowadays. However, given the expected substantial introduction of intermittent sources of energy (i.e. solar, wind), NPPs need to be able to follow the load as stressed by OECD/NEA [5]:

> “a unit must be capable of continuous operation between 50% and 100% of its nominal power (P_n), [...]. Load scheduled variations (should be) 2 per day, 5 per week and 200 per year”.

Therefore NPPs planned today, and operating in the time frame 2025–2100 need to have the manoeuvrability described in Ref. [5]. Several modern NPP designs implement enhanced manoeuvrability, with the possibility of planned and unplanned load-following in a wide power range and with ramps of 5% of nominal power rate per minute [5]. This is, for example, the case of NPPs in France, while older NPPs in other countries (e.g. USA) have more limited manoeuvrability. For example the standard Russian design “VVER–1000” can perform ramps of 3–4% their power rate per minute if the reactor is in the 10–70% of the fuel cycle or 1%–1.5% their power rate per minute if the reactor is in the 70–100% of the fuel cycle [5].

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List of acronyms

AWE	Alkaline Water Electrolysis
DCF	Discounted Cash Flow
CAPEX	CAPital EXpenditures
HTGR(s)	High-Temperature Gas Reactor(s)
HTSE	High-Temperature Steam Electrolysis
LF	Load Following
LWR(s)	Light Water Reactor(s)
NPP(s)	Nuclear Power Plant(s)
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OPEX	OPeration EXpenditures
R&D	Research & Development
SI	Sulphur-Iodine thermochemical
SMR(s)	Small Modular Reactor(s)
WACC	Weighted Average Cost of Capital

1.2. Challenges in load following using nuclear power plants

Currently, NPP follows the electricity demand (from now on “Load Following” - LF) by modifying the reactivity within the core, e.g. by inserting control rods made of neutrons absorbers into the coolant [6]. By doing so, the power is reduced, with a waste of potential energy and a thermomechanical stress on the plant. Moreover, the typical cost breakdown of producing electricity with NPP is [4]:

- Investment, including interest: 59%
- Operation and maintenance: 25%
- Fuel (uranium mining, conversion, enrichment, fabrication): 12%
- Waste management and decommissioning: 4%

Besides investment costs, operation & maintenance costs (mainly personal and insurance) are fixed and independent of the power rate. Therefore unlike fossil-fuelled power plants, there is not a relevant cost saving in operating an NPP at a lower power level due to the substantially fixed nature of costs. Again, opposite to conventional gas-fired plants, where fuel accounts for approximately 70%–80% of the generation cost, nuclear fuel accounts for only about 12% of generation costs [4]. Due to the complexity of the neutron dynamics within the core (fission, absorption by all reactor materials, capture reactions, leaks, poisoning, etc.), the proportionality between power produced and fuel consumed is not linear [6]. A lower power rate does not translate into an equivalent fuel saving. Consequently running a power plant at 50% of its power does not save more than few percentages of its operating cost, while the loss of revenue is proportional to the electricity not produced.

1.3. Load following by cogeneration

As presented in Ref. [7] the fundamental idea of the “LF by Cogeneration” is to meet electricity market demand fluctuation and avoid an economic penalty at the same time. In this configuration, the NPP would work at its nominal power all the time, leaving the primary circuit conditions unchanged. Cogeneration is therefore intended as the production of electrical energy and another valuable product output [8,9]. During the high load/high price hours (usually day-time) the nuclear thermal power is entirely converted into electricity to the grid, while during hours of low demand/low price (usually night-time) the excess thermal energy would produce a valuable by-product. The coupling is particularly virtuous for those co-products that are storable, that require large amounts of energy (heat or electricity) and for which the energy supply represents a significant component of production cost [7].

Virtually *every* facility which requires electricity could be coupled with a standard NPP to support the LF if:

- The power demand is in the region of 500 MW_e–1 GW_e;
- There is an abundance of “input material” to be processed;
- There is relevant market for the end product;
- It can work at full power during the night, and operate at a much lower load during the day. This means that the co-product is storable and daily power cycles do not damage the facility in the long term;

In this paper, we investigate the case of co-production of hydrogen as recommended in Ref. [7]. Since electricity can be more easily transmitted than heat, the proximity with the NPP is not imperative for a hydrogen facility using electricity only. Conversely, the coupling with a hydrogen facility using thermal energy has tighter requirements. An auxiliary facility thermally coupled with an NPP operating in LF mode should:

- Be located reasonably close to the NPP;
- Need a thermal power in the region of 1.5–3 GW_{th};
- Require adequate temperature.

Most of the Light Water Reactors (LWRs - accounting for 89% of the global nuclear capacity [10]) operate in the region of 300 °C; while future high-temperature reactors might operate at higher temperature, for instance, 500 °C for the sodium-cooled fast reactors and 900 °C for high-temperature gas reactors (HTGRs) [11] like the GTHTR300C [12,13]. The NPP temperature is a key parameter because, as later explained (section 2.2), higher the temperature more types of cogenerating facilities are available.

1.4. Why SMRs might be an ideal candidate technology

Small Modular Reactors (SMRs) are a relevant technology for the LF because the overall power at the site level is fractioned. As explained in Ref. [6] and further developed in Ref. [7] a key advantage of adopting multiple SMRs instead of a single large reactor is the intrinsic modularity of an SMR site power output. It is possible to operate all the primary circuits of the SMR fleet at full capacity and switch the thermal power of some of them only, for the cogeneration of suitable by-products. The same could be made with a single large reactor, i.e. some thermal power could be diverted and channelled to the cogeneration process, but getting some steam out of the secondary circuit would compromise the efficiency of the electricity conversion and this would translate into a technical and economic inefficiency. With multiple SMRs, the LF strategy is realised at the site level, rather than at single plant level, by aiming to diverting 100% of the electricity (or 100% of the thermal power) generated by some SMRs to cogeneration purposes and let the remaining SMRs produce power for the electricity market at full regime; in this way the optimal fine tuning of the secondary power circuit is not compromised. Either in the case of full electricity conversion or in full cogeneration operation mode, the efficiency would be maximised, letting the secondary circuits working by-design: indeed, some SMRs could run at the full nominal power and maximum conversion efficiency, while some other would give up producing electricity.

The size of the cogeneration facility is optimised according to