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Adapting the French nuclear fleet to integrate variable renewable energies via the production of hydrogen: Towards massive production of low carbon hydrogen?

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ABSTRACT

Producing low-carbon hydrogen at a competitive rate is becoming a new challenge with respect to efforts to reduce greenhouse gas emissions. We examine this issue in the French context, which is characterised by a high nuclear share and the target to increase variable renewables by 2050. The goal is to evaluate the extent to which excess nuclear power could contribute to producing low-carbon hydrogen.

Our approach involves designing scenarios for nuclear and renewables, modelling and evaluating the potential nuclear hydrogen production volumes and costs, examining the latter through the scope of hydrogen market attractiveness and evaluating the potential of CO_2 mitigation.

This article shows that as renewable shares increase, along with the hydrogen market expected growth driven by mobility uses, opportunities are created for the nuclear operator. If nuclear capacities are maintained, nuclear hydrogen production could correspond to the demand by 2030. If not, possibilities could still exist by 2050.

Introduction

The universal Paris agreement to combat climate change signed in December 2015 provides the foundations for the global movement to switch to low-carbon economies. To fall in line with decarbonisation targets, most energy mixes must undergo transformations with country-specific energy transition pathways. Producing low-carbon hydrogen at a competitive rate is becoming a new challenge and hydrogen systems could play a key role in this perspective.

The French power energy system is currently transitioning towards a more diversified low-carbon mix. One of the starting points of this movement dates back to 2013 when a broad national consultation on energy transition was organised [1]. Several institutions then developed contrasting energy prospective scenarios for France. In line with this approach, the French Energy Transition Act, voted in August 2015, formalised the transition by defining the framework needed to fulfil this French vision [2]. Together, this act and the set of prospective scenarios provide France with a long-term vision

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on energy, by setting targets and by exploring possible pathways leading up to 2050 and beyond. The French power mix is currently composed of a high share of nuclear power which equalled 77% of the total electric production in 2015 [3]. This share is set to be reduced to 50% of the power production from 2025 onwards [2]. Furthermore, the share of variable renewable power from wind and solar currently amounts to 5% of the domestic power production, i.e. approximately 30 TWh per year. In total, the share of renewables equals 18% of the power production, i.e. around 100 TWh per year [3]. The objective for this renewable share is to reach 27% by 2020, 40% by 2030 [2], and so on up to 2050.

From this perspective, France has undertaken a programme to integrate wind and solar into its mix, which are characterised by power variability, uncertainty and priority dispatch, not to mention low variable costs. Such power plants, when introduced massively, represent a number of challenges with respect to maintaining the reliability target level of the power system. They trigger new needs for back-up power, both in the short and long term to answer flexibility requirements. As stated in OECD/IEA document (2014) [4], "*Power system flexibility describes the extent to which a power system can adapt the patterns of electricity generation and consumption in order to maintain the balance between supply and demand in a cost-effective manner*".

In this sense, the flexibility of a power system has two dimensions: the power system has to cope with both power uncertainty and variability from the supply and demand side. The transitional period requires making relevant choices among existing flexibility options to optimise the power system from an economic and technical perspective, as well as to fall in line with decarbonisation targets [4,5].

In a long-term perspective, the introduction of variable renewable energies into power mixes will lead to a shift towards more flexible peak and mid-load power plants at the expense of less-flexible and capital-intensive baseload power plants, such as nuclear power [4–7]. This way, nuclear and variable renewable energies are seen not to fit well together, whereas they can both help reduce greenhouse gas emissions in a power system.

Nonetheless, nuclear power has characteristics compatible with power modulation [8], and already contributes to load following in France because of its high share in the mix. Today, the fleet's level of participation in flexibility is far below its theoretical limitations and the nuclear fleet has the potential to increase its flexibility, both on a reactor-scale and a fleet-scale [9]. In such a context, the French nuclear fleet could be asked to significantly contribute to providing power flexibility services to the power system [9]. However, such an operating mode would mean a more demanding fleet management strategy and a reduction in production with, for some of the scenarios studied herein, a load factor falling as low as 40% [10].

Whereas major operational flexibility options can be found inside the power system (interconnections, demand-side management, storage or flexible dispatchable power plants), coupling the power system with other energy sectors could be a promising complementary solution in a number of energy systems [11–13]. Today, nuclear power plants are mainly used for electricity purposes, but a wider range of applications is possible. In eastern and northern Europe, over fifty nuclear power plants are operating in a cogeneration mode to provide heat for residential or industrial uses [14]. With the recent technical progress made in transporting heat over long distances, nuclear cogeneration has received some renewed interest in France [15]. However, the economic equation of cogeneration is not warranted, being specific to each production site and needs for residential heating are concentrated over a few months in winter [16]. Another nuclear application beyond electricity production is the production of hydrogen, which appears to be easily implemented, as a by-product, within the scope of nuclear power production and in line with a high wind and solar penetration. To achieve the highest possible power plant amortisation level, we propose herein to consider nuclear power flexibility through power use. Based on such an approach, nuclear power plants would be operated at baseload so the power output could be used to produce hydrogen, instead of reducing the plant load when requested by the power system (when nuclear energy is not needed by the grid, this is hereafter referred to as "nuclear excess power"). Hydrogen would then be seen as a vector for interconnection between energy networks (e.g. power and gas systems), all the more so considering hydrogen-based solutions are flexible, which means they have great potential on different time scales to help the power system cope with variability [17].

The final goal of this study is to evaluate the extent to which nuclear could contribute to the production of low-carbon hydrogen in France, while simultaneously contributing to a low-carbon power mix in accordance with the wind and solar share increase. The objective of this paper is three-fold: i/to assess the French hydrogen market segment attractiveness by estimating target costs and prospective volumes; ii/to assess the French nuclear fleet potential for hydrogen production, in terms of volumes and costs, for different wind and solar shares; and iii/to compare the nuclear hydrogen potential supply with the hydrogen market demand, while evaluating the associated CO_2 mitigation potential for France from nuclear hydrogen production.

Hereafter, we focus on one aspect of flexibility: power variability, or in other words, power modulation, then assuming that uncertainty is managed. This paper also does not explicitly deal with long-term adequacy requirements, despite the fact that maintaining the nuclear capacities may also contribute to this need. Nuclear power load following through power use is examined as one option to help variable renewable integration in France. Comparing this option with others falls outside the scope of this paper, even though we are aware that all flexibility options should be developed in a complementary manner, to the extent that they contribute favourably to securing supply and reducing greenhouse gas emissions [5]. Neither the goal is to examine the possible deployment of the diverse hydrogen market segments, but rather to evaluate the hydrogen target cost needed to make it possible to enter these markets, if other conditions (such as regulations, infrastructure deployment, etc.) favour their deployment in France. If a market segment appears to be accessible for nuclear hydrogen production, we will compare it to alternative production process costs (e.g. steam methane reforming (SMR)).

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