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Using surplus nuclear power for hydrogen mobility and power-to-gas in France

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ABSTRACT

Opportunities exist to utilise excess electricity from renewable and nuclear power generation for producing hydrogen. France in particular has a very high penetration of nuclear power plant, some of which is regularly turned down to follow the electricity demand profile. This excess nuclear electricity could be utilised via the electrolysis of water to satisfy the emerging French market for low-carbon hydrogen (principally for mobility applications and the injection of synthetic gas into the natural gas grid). The described analysis examines the use of electrolysers to progressively 'valley fill' nuclear load profiles and so limit the need for turning down nuclear plant in France. If an electrolyser capacity of approximately 20 GW is installed, there is already sufficient excess nuclear electricity available now to meet the predicted hydrogen mobility fuel demand for 2050, plus achieve a 5% concentration (by volume) of hydrogen in the gas grid, plus produce approximately 33 TWh p.a. of synthetic methane (via the methanation of hydrogen with carbon dioxide). The pattern of electrolyser utilisation requires operation mostly at a variable part load condition, necessitating the adoption of flexible, efficient, rapid response electrolysers. The proposed approach more fully utilises the substantial existing nuclear power assets of France and provides an additional pathway to renewables for reducing the CO_2 emissions of hydrogen production.

Introduction

Power system decarbonisation strategies usually rely heavily on achieving greater deployments of wind farms, solar photovoltaic arrays and nuclear power plant. As the penetration levels increase, periods of excess energy (or overgeneration) occur, because of the temporal mismatch between electricity supply and demand [1,2]. Maintaining the dynamic stability of the electricity grid is a fundamental requirement and so electricity surpluses need to be exported immediately, absorbed or curtailed as they occur. Curtailment is more widely practised in grids which have limited or no interconnections to other grids, but in general it is caused by congestion constraints or dynamic stability concerns [3]. A recent study commissioned by the Fuel Cell and Hydrogen Joint Undertaking indicated that excess renewable electricity in Germany could amount to nearly 30% of the total electricity demand by 2050 [4]. This characteristic of increasing amounts of excess energy per MW of installed capacity weakens the case for achieving high penetrations of renewables or nuclear power plant, unless electricity can be readily exported to a neighbouring grid or demand can simply be increased when required [1,2]. Exporting power as a means of increasing

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renewable or nuclear power penetrations has been achieved in some regions (e.g. by Denmark, Germany and France) but, as the magnitude and frequency of excess energy events increase, simply exporting surpluses to neighbouring countries as they occur becomes less viable and more curtailment or absorption (storage) is required.

By convention 'energy storage' has been assumed to comprise only power-to-power storage (P2P) technologies (such as pumped hydro, batteries and flow batteries), where electricity is absorbed at one time and discharged as electricity at a later time. Energy storage technologies can thereby provide power networks with 'peak shaving', 'valley filling' and renewable power management facilities [5]. However, their economic justification depends largely on the prevailing buy and sell prices for electricity in a given region. Unfortunately because P2P storage acts to clip peaks as well as fill valleys in the electrical load profile, its deployment affects adversely the buy/sell price ratio and so, in time, the economic case for its utilisation declines - the law of diminishing returns applies [4].

In this context, it is desirable to widen the scope of the decarbonisation objective to include the absorption of excess energy from the power system for use in the transport and gas systems. The fundamental energy conversion process that is required to achieve this is the electrolysis of water to produce hydrogen. By this means excess generation can be exported by:

- injecting hydrogen (or synthetic methane derived from hydrogen and carbon dioxide) into the gas grid – usually referred to as 'power-to-gas'
- storing hydrogen in electrolyser-based Hydrogen Refuelling Stations (for refuelling fuel cell vehicles)
- storing hydrogen for example in salt caverns for power/heat generation.

Thereby installed capacities of renewables and nuclear power can continue to grow without necessarily causing curtailment to increase, because the total load available is not constrained by the transient demand profile for electricity. By effectively utilising hydrogen to interconnect the power, gas and transport systems, a substantial over-generation of power in the power system can be accommodated and usefully employed [6–10]. Furthermore, in solar-dominated regions the steep ramp in the power requirement from thermal power plant during late afternoon can to some extent be ameliorated [11].

This approach may be applied in many countries as a function of the availability, form and capacity of the gas grid, salt caverns and hydrogen mobility (H2M) infrastructure. In islands with relatively weak electricity grids, or regions with limited interconnections to neighbouring grids (e.g. the UK), the need to implement an indigenous solution must be faced at relatively low renewable power penetrations [12]. Conversely strong continental electricity grids can often transmit excess electricity to another region of lower renewable power penetration; for example, this currently occurs in Southern Germany due to the high solar PV penetration (Fig. 1). However, for all regions, as the renewable or nuclear power penetration grows, it becomes increasingly desirable to utilise the excess electricity locally if curtailment is to be minimised.

France has a remarkably low carbon intensity for electricity generation of 61 gCO_2/kWh_e due to its large nuclear power capacity [14], but it remains heavily dependent on imported fossil fuels for providing heat and mobility. In 2013 transport fuel, natural gas and electricity requirements were similar, amounting to 494, 470 and 498 TWh respectively [15–17]. However, their demand characteristics vary significantly, with the gas demand profile exhibiting the greatest variation across the year (Fig. 2). Outline consideration of Fig. 2 suggests that the French transport and gas systems should be able to readily accommodate any surpluses emerging from the valleys of the national electrical load profile.

In 2013, nuclear power stations in France delivered 402.1 TWh (*i.e.* 80.7% of total electricity generation) [15], with a net total of 51.7 TWh of electricity exported to neighbouring countries, making France the biggest exporter of electricity in Europe [18]. The installed nuclear capacity is presently 63.2 GW and the annual load factor is therefore about 73%. In addition, France has about 40 GW of renewables (including 25.4 GW of hydro, 8.3 GW of wind and 4.7 GW of solar in 2013) [19–23]. In 2015 the French Parliament adopted an energy transition bill (2015-922) which will initiate a number of significant changes to France's energy landscape [24]. The bill's objectives include a 40% reduction in greenhouse gas emissions by 2030 compared with 1990 levels, with a 75% reduction by 2050. Fossil fuel consumption will be reduced by 30% compared with 2012 levels by 2030, with the share of renewables in final energy consumption increasing to 32% (40% of electricity production). Nuclear capacity will be capped at the present level of 63.2 GW, with the share of nuclear energy in electricity production falling to 50% by 2025. This transition away from fossil fuels towards a power system based almost entirely around nuclear and renewables by 2050 implies that France will experience very large amounts of excess renewable electricity and/or excess nuclear electricity.

When compared with other nations employing nuclear power, France is unusual in that it applies a number of methods to control core reactivity in nuclear power plant, so that the total nuclear power generation profile can better follow the daily electricity demand profile as it unfolds [25,26]. However, turning nuclear reactors down on a frequent basis decreases the return on capital investment [27], it reduces the sales income that would otherwise have been achieved had a greater electricity demand existed at these times [26], it incurs plant costs, and it increases waste as boric acid is used to reduce the rate of reaction which increases the volume of effluents generated [28]. Instead if nuclear electricity could be utilised effectively during these periods, the annual load factor could be increased (within the limits driven by plant maintenance) and nuclear power could make a greater contribution to decarbonising the French energy system without needing to increase installed capacity. These periods of turn down, which occur at different times of day/year, represent surpluses of nuclear power. The associated amounts of electrical energy are referred to here for convenience as 'excess nuclear'; this is analogous to 'excess renewables' when renewable power sources need to be turned down/off at times of low demand and high availability. Electrolyser operation to utilise excess energy in a generic power system containing various proportions of renewable and base

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