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Implementation and control of electrolysers to achieve high penetrations of renewable power

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Abstract

The mass deployment of electrolysers, within a power system serving a region of high wind resource, as the enabling mechanism for achieving five key objectives is assessed (that is: a very high installed capacity of wind power plant (WPP); zero wind curtailment during times of low demand; a very high load factor for thermal power plant; an electricity supply of low-carbon intensity; and a hydrogen supply of low-carbon intensity). Three electrolyser implementation cases were simulated for three days characterised mainly by wind availability and emphasis was placed on maximizing the smoothness of the load profile (LF) applied to thermal power plant. If zero-carbon hydrogen is to be produced a daily load factor for thermal power plant of 90% is the upper limit, but load factors of up to 100% are achievable if a carbon intensity of $3\,\mathrm{kgCO_2/kgH_2}$ is permitted. For wind penetrations exceeding approximately 30% of system maximum demand, the electrolyser stock must include implementations close to WPP if curtailment is to be avoided. To achieve very high wind penetrations and very high load factors for thermal power plant requires a large stock of electrolysers—for the system investigated approximately 1.1 MW of electrolyser capacity is required per installed MW of wind power.

Keywords: Electrolysers; Intermittent renewable power sources; Load management; Wind curtailment

1. Introduction

A future power system with a large installed capacity of intermittent renewable power sources (RE) relative to its maximum system demand, also requires a large installed capacity of controllable thermal power plant (TPP) to cover periods of low RE generation. The most prominent example of intermittency is wind power, where the natural fluctuations have raised concerns about achieving high penetrations, especially in islanded power systems. As wind power penetrations, ϕ, have become significant in Denmark, Germany and Spain, these countries have become case studies for the integration of RE in general and wind power in particular [1–9]. In 2003, wind penetration was 20% in Eastern Denmark [10], while in Western Denmark approaches 70% [5]. Predictions for several European countries suggest that in future much higher RE penetrations will be required if carbon abatement targets are to be met, possibly in excess of 100% of the system maximum demand [9,11,12]. Accordingly, the operation of a power system with wind penetrations between 20% and 100% deserves research attention.

If high wind penetrations are to be realised, two carbon emissions problems associated with managing supply intermittency and supply/demand balancing first need to be addressed. Firstly, the requirement for more flexible operation of back-up fossil-fuelled TPP increases with wind penetration in order to balance the intermittent supply with the time-varying demand. Because the accuracy of statistical wind forecasting models decreases with the prediction time, this will have a profound effect on scheduling decisions for TPP and matching TPP operation to demand in power systems with high wind penetrations [13]. Ahead of any predicted decline or increase in RE input, some thermal power plant must be operating even though it may not be required, in case RE availability is not as predicted [14,15]. This increasingly RE-dependent operation of thermal power plant for supply/demand matching will result in

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Nomenclature

CI_e	carbon intensity of electricity, $kgCO_2/kWh_e$
CI_H	carbon intensity of hydrogen, $kgCO_2/kgH_2$
LF	daily load factor of the aggregate thermal load profile, i.e. the ratio of average to peak load across 24 h, %
Y	net daily hydrogen yield, t
P	power, MW
UF	daily utilization factor, i.e. the ratio of average utilisation to the installed capacity across 24 h, %
ϕ	wind power penetration, i.e. the ratio of the installed capacity of wind power plant to the maximum system demand, %
β	installed capacity ratio, i.e. the minimum required installed capacity of electrolyser plant to achieve a given installed capacity of wind power plant, expressed as a proportion

Subscripts

C	consumers
EL	electrolysers
TH	thermal power plant
THEL	of thermal power plant but directed to electrolysers
W	wind power plant output
WC	of wind power plant output but directed to consumers
WDEL	of wind power plant output but directed to demand-side electrolysers
WSEL	of wind power plant output but supplied to supply-side electrolysers

Abbreviations

CCGT	combined cycle gas turbine
DSE	demand-side electrolyser
HHV	higher heating value ($3.54\,kWh/Nm^3$ for hydrogen)
RE	renewable power sources
SSE	supply-side electrolysers
TPP	thermal power plant
WPP	wind power plant

a carbon penalty that increases with wind penetration. Secondly, if at any time wind power plant (WPP) generation exceeds that which can be safely absorbed by the power system, some of the available RE input will need to be curtailed. The value of wind penetration at which such measures need to be taken depends on the exact stock of thermal power plant and the design of the specific power system [4,13]; an islanded power system without significant interconnections is the most challenging to manage. The curtailment of wind farms during periods of high availability but low demand will inhibit the production of low-carbon electricity and thus penalize efforts to achieve high wind penetrations.

Solutions are therefore required for regions of high wind resource to facilitate the achievement of high wind penetrations. One solution, which may be applied for RE sources in general, is to deploy water electrolysers as controllable loads for load management [12,16]. Electrolysis is considered to be the preferred option here because it produces a clean premium value fuel or energy carrier for a wide range of uses, whereas other electricity storage methods (e.g. pumped hydro storage, compressed air, flywheels or flow batteries) provide only “electricity-in, electricity-out” possibilities [17,18]. Few technologies can facilitate carbon abatement across all energy sectors, but water electrolysers can transform any zero-carbon electricity source to a zero-carbon energy carrier suitable for applications, including transport, power generation, industrial heating and chemical production [12]. The markets for hydrogen and its related technologies are potentially huge and hydrogen could, in the long term, replace most other fossil fuels.

In combination with hydrogen storage systems, electrolysers can be used to enable the load placed on thermal power plant to be increased or decreased in time phase with the availability of RE inputs to the power system. Electrolysers can thus be used for hydrogen production both in the case of a fluctuating excess supply (e.g. during prolonged and rising RE generation) and during periods of low electricity demand. The supply of electricity becomes effectively decoupled from the demand in such a way that the operation of thermal power plant depends less on consumer demand. In addition, this form of load management can lead to a higher average utilization rate for preferred low-carbon thermal power plant.

The load factor of this net thermal load profile (LF) acts as an indicator of the carbon performance of the TPP portfolio. The greater the load factor, the flatter the load profile faced by thermal power plant, the more efficient its operation and therefore the lower the carbon intensity of the electricity generated [7,15]. Active load management with electrolysers can then be applied to:

- minimise wind power curtailment,
- maximise the load factor,
- provide a supply of zero- or low-carbon hydrogen.

If a low-carbon (as opposed to zero-carbon) supply of hydrogen is to be produced it is important that the associated carbon intensity value is maintained significantly below that of the conventional hydrocarbon reformation methods that typically yield 6–11 $kgCO_2/kgH_2$ [12].

In order to optimize the operation of a future high ϕ power system, it is necessary to develop an electrolyser control strategy, which takes into account:

- wind power availability,
- the demand for electricity from consumers,