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Wind Farm and Hydrogen Storage Co-location System for Frequency Response Provision in the UK

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1. Introduction

Hydrogen-based storage systems (HSS) are becoming increasingly important in the transition to low-carbon energy systems with the aim of a net-zero carbon future [1, 2]. In particular, they are increasingly explored for the provision of ancillary services by co-location with renewable energy generators, such as wind farms. An HSS for the frequency response provision can work as follows: an electrolyser splits the water into hydrogen (H_2) and oxygen using an electric current passed through a chemical solution, which delivers high-frequency (HF) responses. The H_2 produced at a low-pressure is then pressurised using a compressor and stored in a H_2 storage tank at a high-pressure for later use. To transform the H_2 back to electricity, a fuel cell stack is used, where the H_2 taken from the storage tank reacts with a catalyst, often platinum, stripping it of its electrons that are forced to move along an external circuit, creating electricity for low-frequency (LF) responses [3]. Considering the great investment and the existence of multiple components in an HSS, it is necessary to optimise the capacity and coordination of different HSS components so as to evaluate the techno-economic feasibility of the HSS project.

Previous work by the University of Strathclyde and the Offshore Renewable Energy Catapult has optimised the use of battery energy storage systems (BESS) in delivering frequency response services to the AC grid [4, 5]. From an economic optimisation perspective, the optimal BESS size and operating strategies were determined to maximise the profitability of a wind farm co-located with a BESS for frequency response provision. The aim here is to adapt the optimisation algorithm to explore the feasibility of an HSS in providing Dynamic Regulation (DR) that is one of the end-state frequency response products introduced by the National Grid Electricity System Operator (NGESO) in the GB. Based on the DR market mechanisms and the technical characteristics of HSS components, an operating strategy is developed to dispatch power and hydrogen flows within an onshore HSS that delivers DR responses to the AC grid through the existing connection point of a particular wind farm. The resulting DR payments and other cash flows are translated into the net profit of the HSS co-location project, which is then maximised by a particle swarm optimisation (PSO) algorithm, suggesting the best sizes of the HSS components and the optimal strategy variables for their coordination.

2. Operating Strategy of HSS for DR Service Provision

2.1. Dynamic Regulation Service

The end-state frequency response products introduced by the NGESO, including the DR, allow a provider to tender for either or both HF and LF services with unequal capacities. This will benefit energy storage technologies which have a low round-trip efficiency (e.g., an HSS) by combining a higher HF capacity with

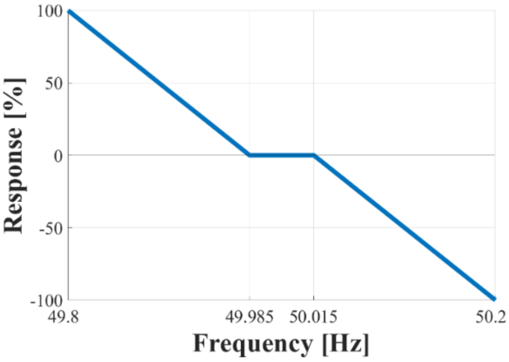


Figure 1: DR response requirements curve.

a lower LF capacity. Furthermore, the DR aiming to slowly correct continuous frequency deviations requires a provider to start providing a response within 2 seconds and reach the full response within 10 seconds [6], which can be met by the electrolyser and fuel cell technologies [7]. In addition, a provider must be able to sustain the full response for at least 60 minutes [6], which specifies the minimum size requirement of H_2 storage tank. The DR response curve required by the NGESO can be visualised by Figure 1 [6].

2.2. HSS Simulation

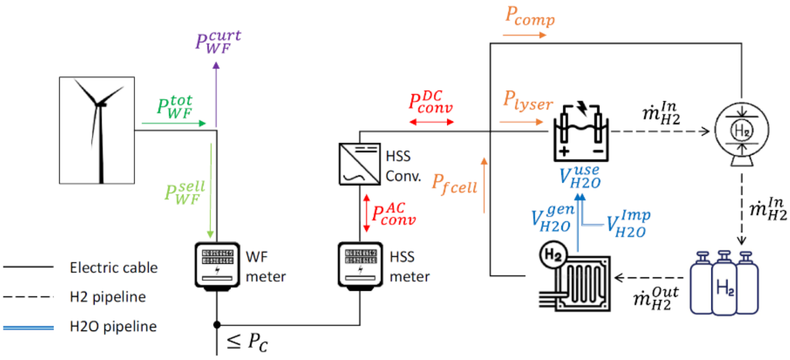


Figure 2: Configuration of wind farm and HSS with a common point of connection. Power, hydrogen and water flows are denoted by P , $\dot{m}$ and V, respectively.

Figure 2 shows the configuration of a particular wind farm and HSS co-location system. The HSS consists of a converter, electrolyser (used during HF provision), compressor, storage tank and fuel cell (used during LF provision). The power, H_2 and water flows within the system must remain balanced. The power flow balance, as illustrated in Figure 2, is formulated using Equation (1) for the AC side, and Equation (2) for the DC side, where P_{WF}^{tot} is the available power output from the wind farm, P_{WF}^{curt} is the curtailed wind power, P_{conv}^{AC} and P_{conv}^{DC} are the converter power on AC and DC sides, P_{WF}^{sell} is the wind power sold, P_C is the ampacity of the connection point, P_{comp} is the power consumed for the compression of the H_2, and P_{lyser} and P_{fcell} denote the electrolyser import and the fuel cell export, which will be driven by HF and LF signals respectively.

$$P_{WF}^{tot} - P_{WF}^{curt} \pm P_{conv}^{AC} = P_{WF}^{sell} \pm P_{conv}^{AC} \leq P_C \tag{1}$$

$$P_{fcell} - P_{lyser} - P_{comp} = \pm P_{conv}^{DC} \tag{2}$$

The H_2 and water flow balance is described by Equations (3) and (4), respectively, where $\dot{m}_{H_2}^{in,i,t}$ and $\dot{m}_{H_2}^{out,i,t}$ are the H_2 flows (kg/h) in and out of the storage tank, and $M_{store}^{i,t}$ is the hydrogen (kg) stored in the asset at time step t in a half-hour settlement period (SP) i. Similarly, $V_{H_2O}^{imp,i,t}$ is the water externally imported (m^3/h), $V_{H_2O}^{use,i,t}$ is the water consumed for the creation of H_2, and $V_{H_2O}^{gen,i,t}$ is the water generated when the H_2 is converted to electricity.

$$M_{store}^{i,t} = M_{store}^{i,t-1} + (\dot{m}_{H_2}^{in,i,t} - \dot{m}_{H_2}^{out,i,t}) \cdot \Delta t \tag{3}$$

$$V_{H_2O}^{imp,i,t} = \max(\sum V_{H_2O}^{use,i,t} - \sum V_{H_2O}^{imp,i,t-1} - \sum V_{H_2O}^{gen,i,t} , 0) \tag{4}$$

2.3. Operational Baseline Calculation

In the end-state frequency response service markets, a provider needs to inform the NGESO of its operational baseline over a future SP. This allows an energy-limited provider to manage its state of energy (SOE) during the provision of frequency response [8]. The delivery contracts of DR services are allocated in 4-hourly electricity forward agreement (EFA) blocks, each consisting of 8 SPs. According to the SOE rules specified by the NGESO for energy-limited providers [8], the HSS is designed here to submit its operational baselines for future SPs with the objective of restoring its hydrogen storage back to the target storage region before the start of the subsequent contracted EFA block.

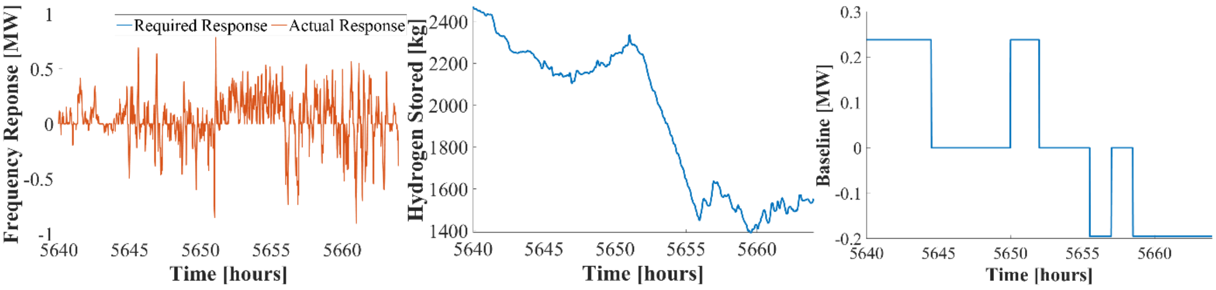
3. Optimisation Results and Discussion

The HSS optimisation algorithm is tested here based on a particular 76 MW wind farm in the GB. The HSS component sizes, LF and HF DR tender capacities and the target region for hydrogen storage restoration are co-optimised to maximise the equivalent annual benefit (EAB) of the wind farm and HSS co-location project, based on a DR unit price of £17/MW/h and the electrolyser/fuel cell unit prices predicted for 2030 [9]. Table 1 lists the optimised technical variables and the resulting EAB and internal rate of return (IRR) respectively, which suggest a profitable HSS co-location project with a notable IRR of 12%. Furthermore, it is noted that the ratio of the LF tender capacity (16 MW) to HF tender capacity (50 MW) is close to the ratio of the electrolyser efficiency (18 kg/MWh) to fuel cell efficiency (60 kg/MWh). This demonstrates that the best tender capacities of LF and HF services are very reliant on the efficiencies of electrolyser and fuel cell.

Table 1: Results of PSO-algorithm Simulation.

Variable	Value
Net Present Value (NPV) [£]	11,440,465
Equivalent Annual Benefit (EAB) [£]	1,332,662
Internal Rate of Return (IRR) [%]	12
Electrolyser [MW]	46.72
Fuel Cell [MW]	17.09
Low Frequency Power [MW]	16
High Frequency Power [MW]	50

The optimisation-based simulation of DR responses, baselines and H_2 storage levels over a particular day is shown in Figure 3, respectively. Figure 3(a) shows that the required DR responses are completely delivered by the HSS. The resulting H_2 storage variation is shown in Figure 3(b) where the stored H_2 firstly declines slightly, followed by a slight increase as the HF responses are delivered, and the electrolyser creates the H_2. The stored H_2 then decreases quite a bit due to the continuous LF events over 5651 h to 5655 h, where the fuel cell converts the H_2 back to electricity. Figure 3(c) illustrates the corresponding changes in baselines from more electricity export (for H_2 release) at the start of the day, where the H_2 storage is higher, to electricity import (for H_2 recovery) towards the end of the day, where the H_2 storage is lower. These results illustrate the effectiveness of the model and operating strategy in managing the HSS for DR provision and operational baseline submission.



(a) (b) (c)

Figure 3: (a) The actual delivery and requirements of DR (MW), (b) hydrogen storage levels (kg) and (c) operational baselines of the HSS simulated over a particular day, shown from 5640 h to 5664 h.

Figure 4(a) compares the DR response curve against the actual delivery throughout the 15-year project lifespan, which covers a wide frequency range. The HSS is shown to give a better performance in HF delivery than LF delivery, as can be seen by the higher density of the dots falling below the DR curve on the LF side. Figure 4(b) shows the distribution of H_2 storage levels over the full 15 years, which tends to be Normal, slightly skewed to the left. Furthermore, the storage tank is almost empty for around 0.02% of the time, which explains the worse performance in LF DR delivery.

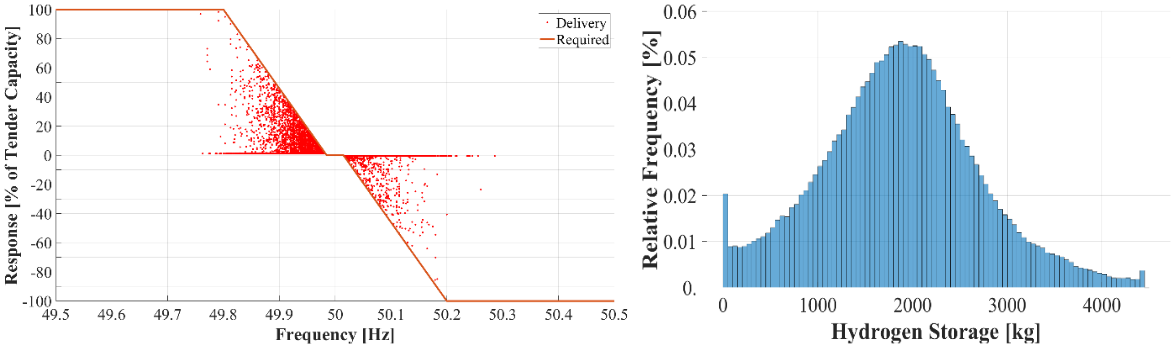


Figure 4: (a) The DR response curve against the actual delivery and (b) the relative frequency of hydrogen storage levels simulated for the full 15 years.

4. Conclusions

This paper has developed an economic optimisation algorithm to optimise the co-location of a wind farm with an onshore hydrogen-based storage system (HSS) for the provision of Dynamic Regulation (DR) frequency response in GB. A particular operating strategy has been designed to use an electrolyser and fuel cell to provide high- (HF) and low-frequency (LF) DR responses, respectively, as well as manage the hydrogen storage via operational baselines, while respecting the balance of power, hydrogen and water flows within the co-location system. The effectiveness of the HSS optimisation algorithm has been examined based on a particular 76 MW wind farm, combined with the unit prices of the electrolyser and fuel cell predicted for a 2030 scenario. The co-located HSS has been suggested to tender for 16 MW LF and 50 MW HF DR, indicating a strong correlation to the fuel cell and electrolyser efficiencies. Although the low round-trip efficiency and limited storage size of the HSS resulted in the occurrence of under-delivery events and penalties (especially for LF DR), the optimised HSS co-location project is predicted to be profitable for DR provision, showing a notable IRR of 12%.

Building on the present work, the operating strategy will be developed further to include the power consumed for keeping the electrolyser at the correct temperature and pressure in a hot-standby mode. Furthermore, active interaction between wind farm and HSS will be explored by use of an additional power converter to enable their energy interchange. In addition, the use of the hydrogen produced in HF events for local hydrogen supply will be investigated as an alternative to the hydrogen re-electrification for LF delivery.

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