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Resilience Assessment of Offshore Wind-to-Hydrogen Systems [†]

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Abstract: Low-cost green hydrogen production will be key in reaching net zero carbon emissions by 2050. Green hydrogen can be produced by electrolysis using renewable energy, including wind energy. However, the configuration of offshore wind-to-hydrogen systems is not yet standardised. For example, electrolysis can take place onshore or offshore. This work presents a framework to assess and quantify which configuration is more resilient, so that security of hydrogen supply is incorporated in strategic decisions with the following key findings. First, resilience should be assessed according to hydrogen supply, rather than hydrogen production. This allows the framework to be applicable for all identified system configurations. Second, resilience can be quantified according to the quantity, ratio, and lost revenue of the unsupplied hydrogen.

Keywords: hydrogen; offshore wind; resilience; robustness

1. Introduction

Reaching net zero carbon emissions by 2050 is a global challenge and goal. Meeting this will require innovative solutions in the way many activities are performed. One of them is the production of green hydrogen at an affordable level and at scale. Green hydrogen is produced by renewable energy resources, such as wind energy. The underlying process to make hydrogen from offshore wind is electrolysis, where the electricity produced by offshore wind is used to split water into hydrogen and oxygen.

The United Kingdom has a long history and great potential for electricity production from offshore wind energy, with more than a four times increase in operational offshore wind capacity in the decade 2012–2022 [1]. Even though early research around hydrogen production from offshore wind is ongoing [2–4], there are many questions that need to be understood to produce hydrogen from offshore wind at scale—should electrolysis take place offshore or onshore? How can these systems be controlled? Will the offshore wind farm be connected to shore through a pipeline, a cable, neither or both? If a significant failure occurs, which configuration is more resilient, and how can this be quantified?

To this end, there are two aspects of focus in this paper. First, a range of configurations of offshore wind-to-hydrogen systems is introduced. Second, a framework on how to assess and quantify the resilience of such systems is presented.

This paper is structured as follows. Section 2 introduces offshore wind-to-hydrogen system configurations. Section 3 presents the framework to assess and quantify the resilience of such systems. Section 4 concludes this work.

2. Offshore Wind-to-Hydrogen System Configuration

The concept of an integrated wind turbine–electrolyser systems is relatively new, with pilot projects beginning to be deployed this year [5]. In this section, the challenges

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and opportunities are explored, regarding the different configurations of these integrated systems. The focus is on the integration aspect itself, looking how best to connect wind turbines and electrolysers. The main offshore wind farm–electrolyser configurations are as follows:

Centralised offshore—where there is a single (or a few) large electrolyser(s) on separate platforms connected to the windfarm.

Centralised onshore—where there is a single (or a few) large electrolyser(s) onshore, which has an electrical connection from the wind farm.

Decentralised offshore—where each turbine has its own electrolyser system (Figure 1)

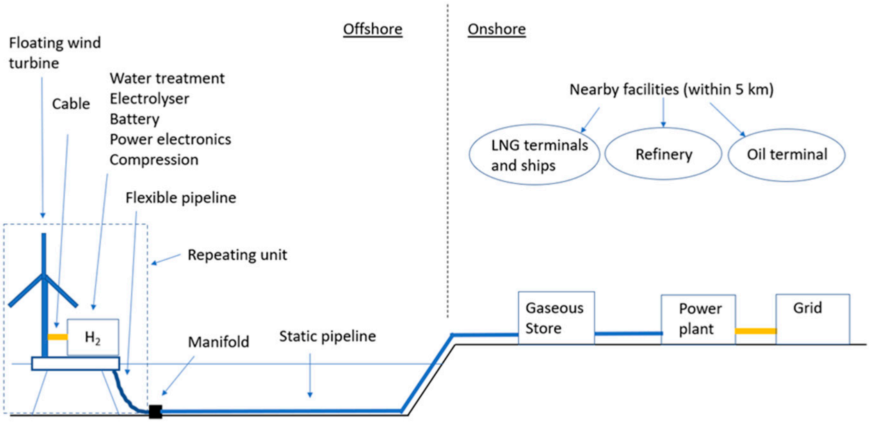

Figure 1. Decentralised offshore electrolysis topology.

More information on the configurations above can be found in [6]. The overall system integration and engineering challenges are discussed considering the following.

Electrical system—Wind farms that export electricity to the grid need power electronics and potentially substations to match the grid voltage and frequency. They will also be subject to grid-induced curtailment. On the other hand, wind farms that connect directly to electrolyser systems will probably have a micro-grid. These will need at least one energy storage system to balance the electrical system on a second-by-second basis, but also on a day-to-day basis, e.g., to meet standby power losses. These wind farms may also need black-start capability.

Energy export method—Electrical cables, hydrogen pipelines and energy shipping each have different costs and energy carrying capacities (e.g., GW per cable vs. GW per pipe). They will also have different characteristics. Cables and pipelines connect two fixed points, while ships offer flexibility on where energy is sent and sold.

Additional contributions to the energy system—For off-shore scenarios, hydrogen pipelines and energy-carrying ships can be used as energy storage systems, which can be used to help balance supply and demand of energy. On the other hand, onshore electrolysers could interact with the electrical network to provide ancillary services or potentially buy cheap electricity from the grid, increasing hydrogen production at a marginal cost.

Ability to tie into other infrastructure—Hydrogen systems could potentially tie into energy storage systems in the form of subsea geological features. Hydrogen systems could also be useful when supplying wind energy to places with a demand for chemical energy, such as ports, airports, and industrial clusters. On the other hand, electrical systems could tie into existing substations, such as those beside decommissioned nuclear power plants.

Time to deployment—In addition to the wind farm, the energy export system will take time to build and deploy. Additionally, most export routes will need new onshore receiving systems to be built. For example, electricity export will require a grid connection. For hydrogen pipelines, the onshore component could be a distribution system, or connection to a transmission system. For energy shipping, this could be a port that receives the energy. Some export routes may be able to tie into existing infrastructure.

Maintenance requirements—Electrolysers, compressors, storage tanks and the other required hydrogen equipment add to the maintenance burden of any wind turbine system. This additional maintenance is amplified if the hydrogen equipment is based offshore, with every trip to a site having a much higher cost when compared to an onshore site.

The next section presents the framework to assess the resilience of such systems.

3. Resilience Assessment Framework and Quantification Metrics

The assessment framework for resilience greatly depends on the system in question. For example, the work in [7] studied resilience and robustness of offshore windfarms. For offshore wind-to-hydrogen systems, current work has focused on reliability [3] and sensitivity and risk analysis of costs associated with these systems [4]. Even though resilience assessment of components of offshore wind-to-hydrogen systems have been studied, there is an absence of work on resilience assessment of the system, perhaps because their configuration is not yet standardised (as explained in Section 2).

To assess resilience of offshore wind-to-hydrogen systems, it was important to first define the boundaries of the system in question. Due to the wide range of potential topologies of offshore wind-to-hydrogen systems, this was set to the point of hydrogen *supply*. This is at the point where hydrogen is either injected into the gas network or stored and transported elsewhere (shown in Figure 2). Anything happening beyond that point that causes the hydrogen not to reach the end users is outside the system's boundaries and should not be considered as a hindrance of the system's resilience. In Figure 2, end users may be refuelling hubs, steel manufacturers, or other hydrogen users [2].

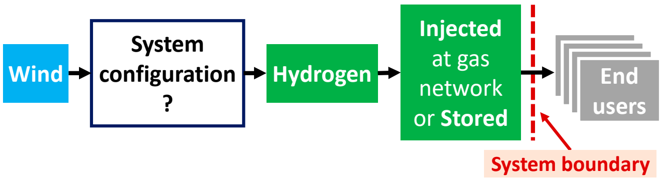

Figure 2. The boundary of the system for the resilience assessment framework, regardless of the offshore wind-to-hydrogen system configuration.

It is worth noting that, initially, the hypothesis was that resilience should be assessed according to the lost hydrogen *production* (rather than *supply*) due to unprecedented events. However, this hypothesis was ruled out, as it would exclude the decentralised offshore electrolysis configuration (Figure 1). For example, if the pipeline stops operating, hydrogen *can still be produced* offshore but it *cannot be transferred* to shore.

Setting the system's boundary was crucial, as this naturally evolved the definition of resilience for offshore wind-to-hydrogen systems. The definition is based on [8], which assesses resilience of integrated energy systems:

Resilience of an offshore wind-to-hydrogen system is the ability to supply hydrogen at the level required with minimal interruptions despite unprecedented events. Unprecedented events are incidents that occur within or beyond the system bounds and can put the system under stress and limit or curtail hydrogen supply. These may include equipment failures, cascade phenomena, and extreme weather events.

It was also identified that resilience of these systems can be quantified according to how robust they are when unprecedented events occur. In fact, ref. [9] describes that resilience is composed of a system's robustness, resourcefulness, and recovery abilities. Based on this, the definition of robustness is [9]:

Robustness of an offshore wind-to-hydrogen system is the ability to supply hydrogen at the level required despite unprecedented events. This depends on the available capacity of hydrogen storage in cases where hydrogen supply from direct production is decreased or curtailed, and the time required to isolate or bypass any issues to restore hydrogen supply for the end users while any issues are being repaired.

Given this framework, three metrics were developed to quantify resilience of offshore wind-to-hydrogen systems according to their level of robustness when unprecedented events occur:

'Hydrogen-not-supplied': this metric describes the quantity of hydrogen that is not supplied and can be quantified in kg H_2 or kWh H_2.

'Ratio of hydrogen-not-supplied': this metric describes the percentage (%) of unsupplied hydrogen and can be used to compare system configurations that produce different levels of hydrogen or to simply quantify that ratio.

'Lost revenue due to hydrogen-not-supplied': this metric represents the financial loss due to unsupplied hydrogen and describes currency units (e.g., GBP/EUR).

Figure 3 below summarises this section and shows paths for future work.

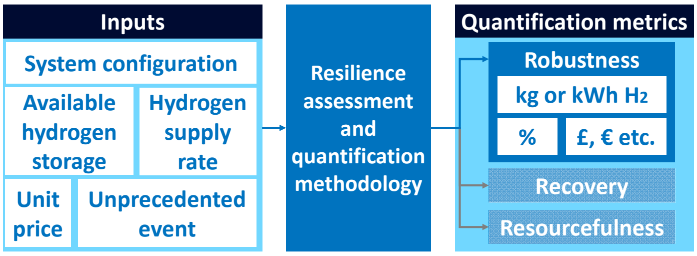

Figure 3. The resilience assessment framework for offshore wind-to-hydrogen systems. Inputs represent the required information and quantification metrics of the outputs of the framework. At the heart of the framework is the methodology that links the inputs to the quantification metrics.

4. Conclusions

This work presented background on the integrated wind turbine–electrolyser systems and presented an initial analysis on how to assess these systems from a perspective of resilience. In terms of resilience assessment, three key areas were identified. First, resilience should be assessed according to the hydrogen *supplied* (rather that the hydrogen *produced*) to be applicable for different system configurations. Second, robustness is part of the system's resilience. Third, resilience quantification metrics can describe the quantity, percentage, and lost revenue of the unsupplied hydrogen. Future work can extend the proposed framework to incorporate the system's ability of recovery and resourcefulness (shown in Figure 3 above).

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