Producing green hydrogen from wind and solar energy: case study

Overhyped or underestimated? Across the globe, governments are betting on hydrogen – especially if it can be produced from wind and solar power as part of the net zero transition. While some developers are racing to announce GW-scale projects that will take decades to come online, others are considering more small-scale, near-term opportunities.

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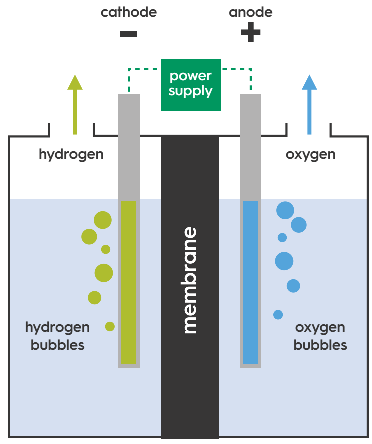
In the UK, it is increasingly challenging to obtain grid connections for wind and solar farms, and there is a strong case for using green hydrogen to help integrate more renewables into our energy system and avoid hefty curtailment losses during periods of high wind and low demand.

The appetite for green hydrogen and other so-called "power-to-x" projects fits in with a broader trend towards co-location of different renewable energy generation technologies as well as battery storage.

In this article, we explore some of the key questions developers are grappling with:

- **How much green hydrogen can be produced from co-located wind and solar electricity at a specific site?**
- **What is the optimal sizing for electrolyser capacity with respect to renewable generation capacity?**
- **To what extent can electrolysers help to mitigate renewable energy curtailment?**



Electrolysis

THE BASICS

Electrolyser technology has existed since around 1800. Electricity is used to split water into hydrogen and oxygen gas. While there are different types of electrolysers, the dominant design for co-location with renewables uses so-called PEM (proton exchange or electrolysis membrane) technology, which is particularly well suited to cope with intermittent input power levels.

Present-day PEM electrolysers are modular devices that can be scaled to meet project requirements. A typical module has a nominal input power rating in the range of 2-5MW. Taking into account conversion efficiencies, this implies a H_2 production rate of around 400-430 kg/day/MW.

Put simply, a typical 5MW electrolyser can produce H_2 at a rate of around 0.025kg/s – provided it consistently receives 5MW of input power.

Of course, wind and solar power are intermittent. Their power output can fluctuate from zero to rated power over short timescales and follows time of day and seasonal patterns. The term "capacity factor" is defined as follows:

Capacity factor = (Actual generation over a year) / (Rated power x 8760h)

Broadly speaking:

- A typical UK onshore wind farm has a capacity factor of 30-45%.
- A typical UK solar farm has a capacity factor of 10-15%.
- An electrolyser must be run at a capacity factor (or utilisation) of at least 60% to be commercially viable.

Determining the right combination of each technology therefore requires site-specific analysis.

SIZING OPTIMISATION FOR A WIND/SOLAR/H2 PROJECT IN SCOTLAND

In this case study, we selected a site in the Scottish borders, which remains one of the most active renewable energy development areas in the UK and can be considered a prime location for green hydrogen co-location due to existing grid constraints.

For the purpose of this analysis we have focused on a project concept where the renewable generator is physically co-located with the electrolyser facility and is connected to the electricity grid. This is representative of the majority of projects we have been supporting UK developers with.

The relative sizing of each technology is key. This determines not only the electrolyser capacity factor, but also the periods when the renewable power output cannot fully be absorbed by the electrolyser and has to be fed into the electricity grid, or curtailed.

To assess different sizing configurations and technology combinations, we created a time series model as shown in **Figure 1**. This allowed us to assess three scenarios:

- Scenario 1: Hydrogen created from standalone 50 MW wind farm
- Scenario 2: Hydrogen created from standalone 50 MWac solar farm
- Scenario 3: Hydrogen created from 100 MW wind/solar hybrid farm

To capture both short-term and long-term patterns in the wind and solar resource, the analysis covered a 20-year period with hourly resolution data.

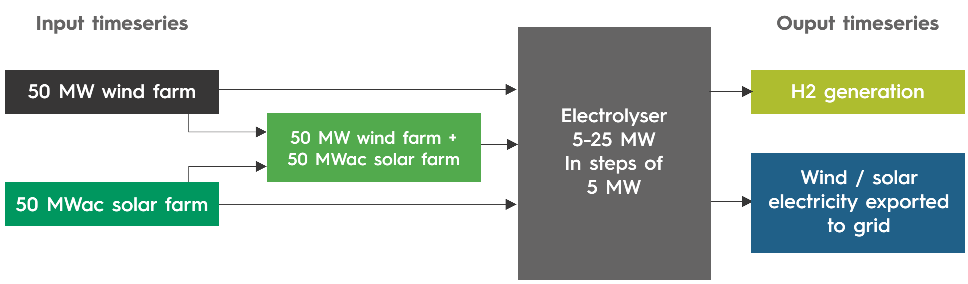
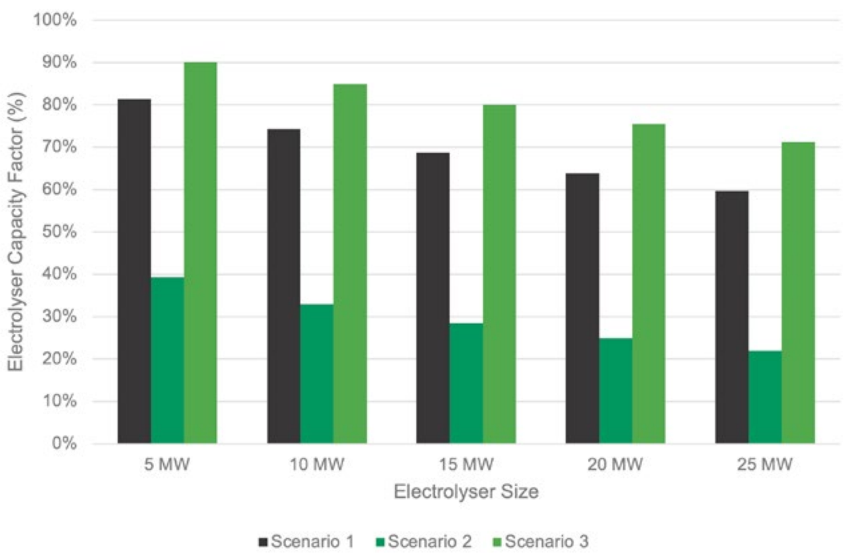


Figure 1: Hybrid time series model

HEADLINE RESULTS

The long-term annual average electrolyser capacity factors are shown for each scenario in **Figure 2**.

Figure 2: Electrolyser utilisation for different sizing scenarios

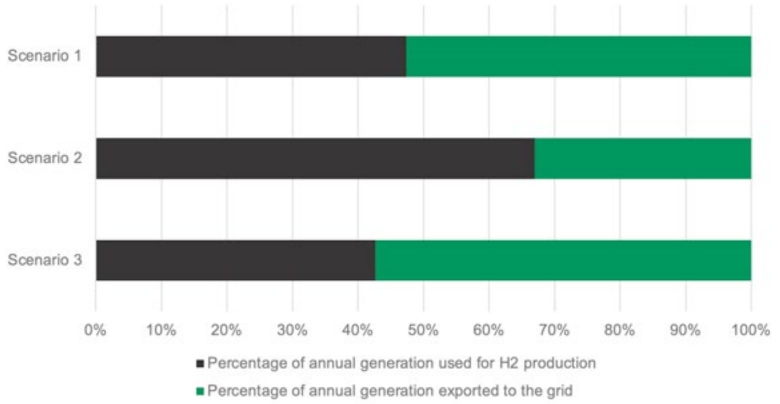


Clearly, the standalone wind farm (Scenario 1) can produce more hydrogen than the standalone solar farm (Scenario 2) due to wind and solar resource levels in Scotland. In this location, the electrolyser can be sized at up to half of the wind farm's capacity to ensure sufficient utilisation.

Conversely, the standalone solar farm would likely not be a viable option for hydrogen co-location as even a small electrolyser would stand idle for the majority of the year. Scenario 2 is therefore not considered a priority in our subsequent analysis. However, combining wind and solar generation (Scenario 3) allows the electrolyser utilisation to be boosted by around 10% compared to the standalone wind scenario.

In all scenarios, there is a significant proportion of electricity that is not converted to green hydrogen and exported to the grid instead. It is assumed that the grid connection is sized to match the renewable generator's rated power, i.e. there is no curtailment risk at this stage. The annual percentage of the generation used for hydrogen production and percentage of generation exported to the grid following hydrogen production is displayed in **Figure 3**, for a 15 MW electrolyser.

Figure 3: Different uses of generation (15 MW electrolyser capacity assumed)



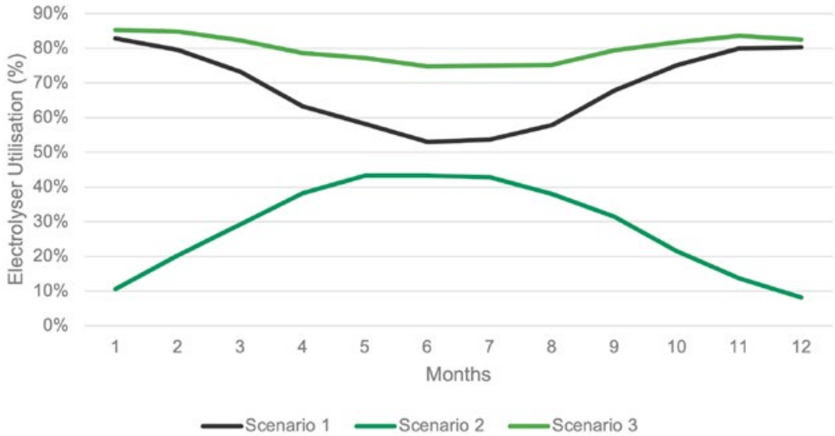
BENEFITS OF COMBINING WIND AND SOLAR GENERATION

Co-locating wind and solar can be very beneficial as their respective generation tend to peak at alternative times of day and year. A hybrid facility can achieve a more consistent seasonal generation profile, compared to the either of the two technologies in isolation. Wind farms tend to have higher generation during the winter months and night-time hours.

In contrast, solar farm generation peaks during the summer months and in day-time hours.

Figure 4 shows how the combination of the wind and solar generation results in a more consistent green hydrogen production profile throughout the year, using a 15 MW electrolyser as a representative example.

Figure 4: Seasonal electrolyser utilisation (15 MW electrolyser capacity assumed)



INTER-ANNUAL VARIABILITY OF HYDROGEN PRODUCTION

The Inter-Annual Variation (IAV) of the electrolyser capacity factor is important to consider because it represents the typical variability of green hydrogen production from year to year. If a project is committed to delivering a minimum volume of hydrogen to an offtaker each year, the risk of falling short of this threshold must be understood. If the project is unable to import electricity from the grid to power the electrolyser and make up the shortfall, it may need to compensate the offtaker for having to source additional hydrogen from an alternative provider.

Intuitively, the IAV for green hydrogen is primarily driven by the wind and solar resource. Combining the two technologies ensures a more consistent annual production as a poor wind year typically coincides with a strong solar year, and vice versa. This is illustrated in **Figure 5**.

The variability of the annual capacity factor for a 15 MW electrolyser is illustrated in the following table.

Annual electrolyser capacity factor	Scenario 1: 50 MW wind farm	Scenario 2: 50 MWac solar farm	Scenario 3: 50 wind farm + 50 MWac solar farm
Average	69%	28%	80%
Minimum	64%	27%	76%
Maximum	75%	31%	84%
Inter-Annual Variation	3.8%	3.4%	2.2%

Variability of the annual capacity factor for a 15 MW electrolyser

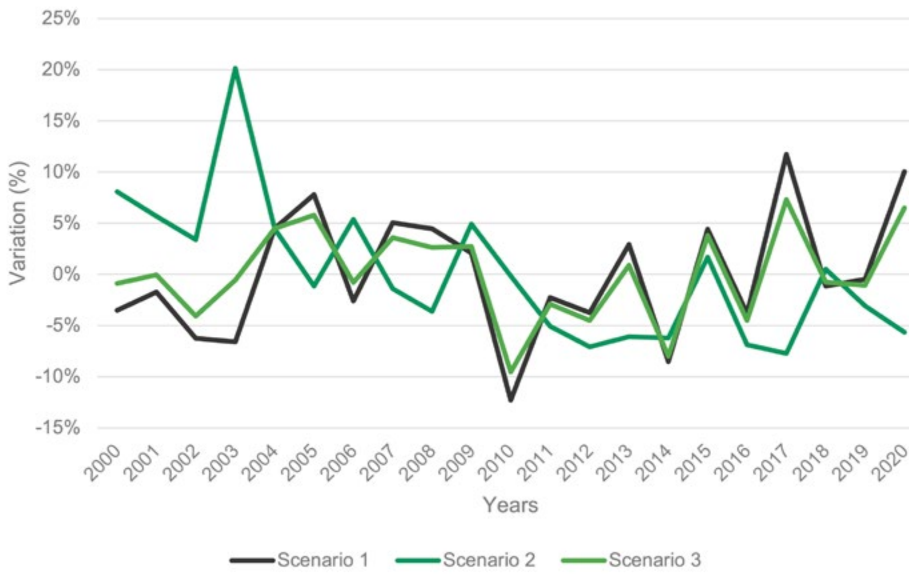


Figure 5: Inter-annual variation of hydrogen production

IMPLICATIONS FOR HYDROGEN TRANSPORT AND STORAGE REQUIREMENTS

Whether the offtaker is located immediately adjacent to the electrolyser facility or the hydrogen has to be transported to the offtaker via tanker trucks, there will likely be a requirement to store a certain volume of hydrogen on-site.

Assuming that the generated hydrogen is transported away from site on a daily frequency, our analysis suggests that a maximum on-site hydrogen storage capacity of around 260-270kg would be required in our case study for a 15 MW electrolyser. This falls within the capacity of a typical tube trailer carrying compressed hydrogen gas [1].

	Green hydrogen production from 15 MW electrolyser	
	(kg)	(kg / MW electrolyser capacity)
Scenario 1: 50 MW wind farm		
Average daily H2 production	189.2	12.6
Maximum daily H2 production	221.5	14.8
Scenario 3: 50 MW wind farm + 50 MWac solar farm		
Average daily H2 production	261.5	17.4
Maximum daily H2 production	265.7	17.7

USING GREEN HYDROGEN TO ABSORB RENEWABLE ENERGY CURTAILMENT

Grid-connected wind and solar farms usually have a Maximum Export Capacity (MEC), which defines how much energy can be exported to the grid at any one time. Oversizing the wind or solar farm with respect to the MEC can be attractive if there is sufficient land available to support a large scheme, but grid capacity can only be secured for a fraction of the project's generation potential.

If a project is oversized with respect to the MEC, there will be times when its generation has to be curtailed and the associated electricity (and revenues) are lost. This is particularly relevant for wind farms which can experience long periods of operating at rated power. Many developers are exploring both battery storage and electrolysers to mitigate against this risk.

To assess a green hydrogen facility's ability to absorb curtailment losses for a standalone wind farm, we modelled multiple scenarios representing an overbuild ratio between 1.3 and 1.7 (where the overbuild ratio is calculated as the renewable energy generator's maximum output divided by the MEC).

The monthly utilisation for three difference electrolyser capacities was calculated for each overbuild ratio, assuming that only curtailed generation is used for hydrogen production. **Figure 6** clearly shows that even in the more aggressive overbuild scenario, electrolyser utilisation falls significantly short of the benchmark needed for a viable business case.

[1] https://hydrogeneurope.eu/wp-content/uploads/2021/11/Tech-Overview_Hydrogen-Transport-Distribution.pdf

Figure 6: Seasonal electrolyser utilisation from curtailed generation only

Figure 7 further illustrates the curtailment challenge. A smaller electrolyser may achieve higher utilisation, but also leads to significant periods where the excess wind generation cannot be fully converted to hydrogen. In the 5 MW electrolyser scenario, less than 40% of curtailment is avoided.

Our advice to developers is clear – **hydrogen is not a silver bullet to mitigate against wind farm curtailment**. A flexible approach will likely be needed, where wind farm generation is allocated to hydrogen production or export to the grid on an hour-by-hour basis.

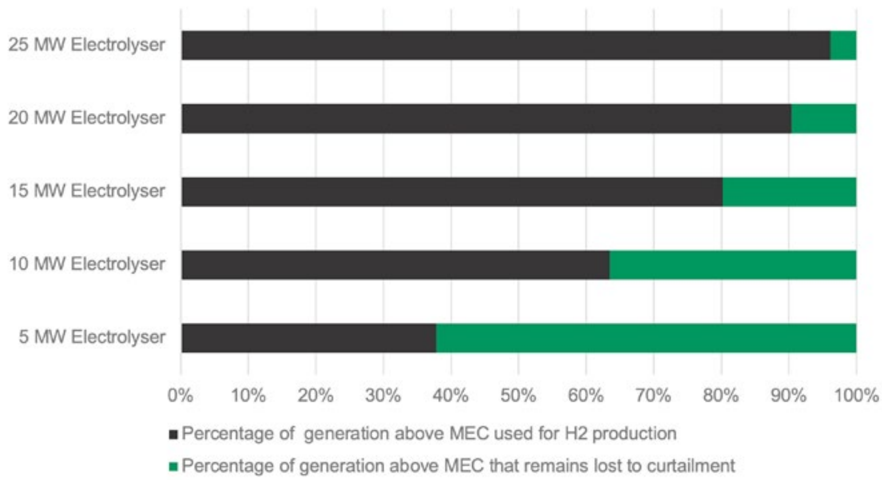


Figure 7: Ability of different electrolyser sizes to absorb wind curtailment for a 1.7 overbuild ratio

INTRODUCING BATTERY STORAGE TO INCREASE ELECTROLYSER UTILISATION

The analysis presented in this case study assumes that wind or solar electricity is used in the following order of priority:

1. Electricity is used for green hydrogen production

2. Electricity is exported to the grid

3. Electricity is curtailed (if both the MEC and the electrolyser rating are exceeded).

As discussed above, in reality, a more complex optimisation strategy will be required. Introducing Battery Energy Storage Systems (BESS) could further help to improve the business case.

Co-location of renewable energy and BESS is increasingly common, with the BESS primarily used to trade electricity on the day-ahead market as well as provide ancillary and balancing services to the grid.

However, a BESS could also be used to peak shift wind and/or solar generation to ensure a smoother operating profile for the electrolyser facility, absorb curtailment, and ultimately increase the electrolyser capacity factor. This would be especially relevant for any off-grid projects that are unable to export excess electricity to the grid.

Natural Power will explore BESS sizing considerations for integration with green hydrogen in a future case study.

CONCLUSIONS

This paper presents a case study assessing various options for combining wind, solar and green hydrogen infrastructure.

With a growing number of developers pursuing this type of hybrid project, we highlight the following key findings:

- **Electrolysers need to be run at a relatively high capacity factor (60%+) to be commercially viable. This is the main driver for sizing considerations.**
- **In markets like the UK, wind and hydrogen are better suited to co-location than solar and hydrogen. However, the highest electrolyser utilisation is achieved by combining wind and solar generation, due to the complimentary resource profile.**
- **While electrolysers can help to absorb curtailment losses in a scenario where the renewable generator is oversized with respect to its grid connection, this is unlikely to support a viable business case in isolation.**
- **Understanding inter-annual variation as well as the average and maximum daily hydrogen production profile is key to hydrogen storage and offtake considerations.**
- **Adding battery energy storage could help to achieve a smoother hydrogen production profile and higher electrolyser utilisation.**

Natural Power can provide support to renewable energy and green hydrogen developers on a wide range of topics, from permitting and grid connections to water use and transport considerations. For more information, please contact:

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