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A Wind to Hydrogen Model for Design of Off-Grid Wind to Hydrogen Systems

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Overview of Work

To investigate the impact of control on off-grid wind to hydrogen system and to facilitate a coordinated design and optimisation process, a wind to hydrogen model has been developed that comprises four inter-connected parameterised modules representing the wind farm, the electrolyser, the battery storage and the controller. The modular design makes the model easily adaptable for different plant configurations.

The model uses inputs of hourly average wind speeds for a site and outputs total hydrogen production, electrolyser degradation, and battery degradation. An overview of the model is presented here.

The components of the model have been verified against other work. The model has then been used to investigate the difference in electrolyser degradation when using centralised or decentralised approaches. Initial results show that a centralised approach has very large benefits for the electrolyser lifetime and some advantage for hydrogen production and the battery sizing and lifetime.

Future work will:
- Enhance the model with additional features (e.g. alternative power sources)
- Optimise system design using more advanced control and machine learning approaches

Accronyms

PEM - Proton Exchange Membrane
LMO - Lithium Manganese Oxide
SoC - State of Charge
DoD - Depth of Discharge

Thanks

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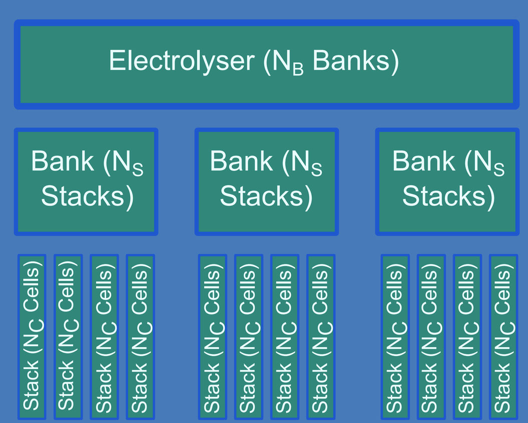
Electrolyser Modelling and Verification

The electrolyser modelled is Proton Exchange Membrane (PEM) electrolyser, for which the cell design is specified using the key parameters listed on the left. These values are inserted into a model based on [1], to create a relatively simple but verified model for electrolyser cells.

The topology of the electrolyser is then designed as shown in the diagram on the right, with each electrolyser divided into banks, and each bank divided into stacks. The user can select the hierarchical level at which the power flow is controlled.

Cell Design Parameters:

A_{Cell} - Active cell area
i_D - Current density of cell
V_{Nom} - Nominal cell voltage
e_{min} - minimum potential
r_0 - cell reference resistance
dr_t - gradient constant

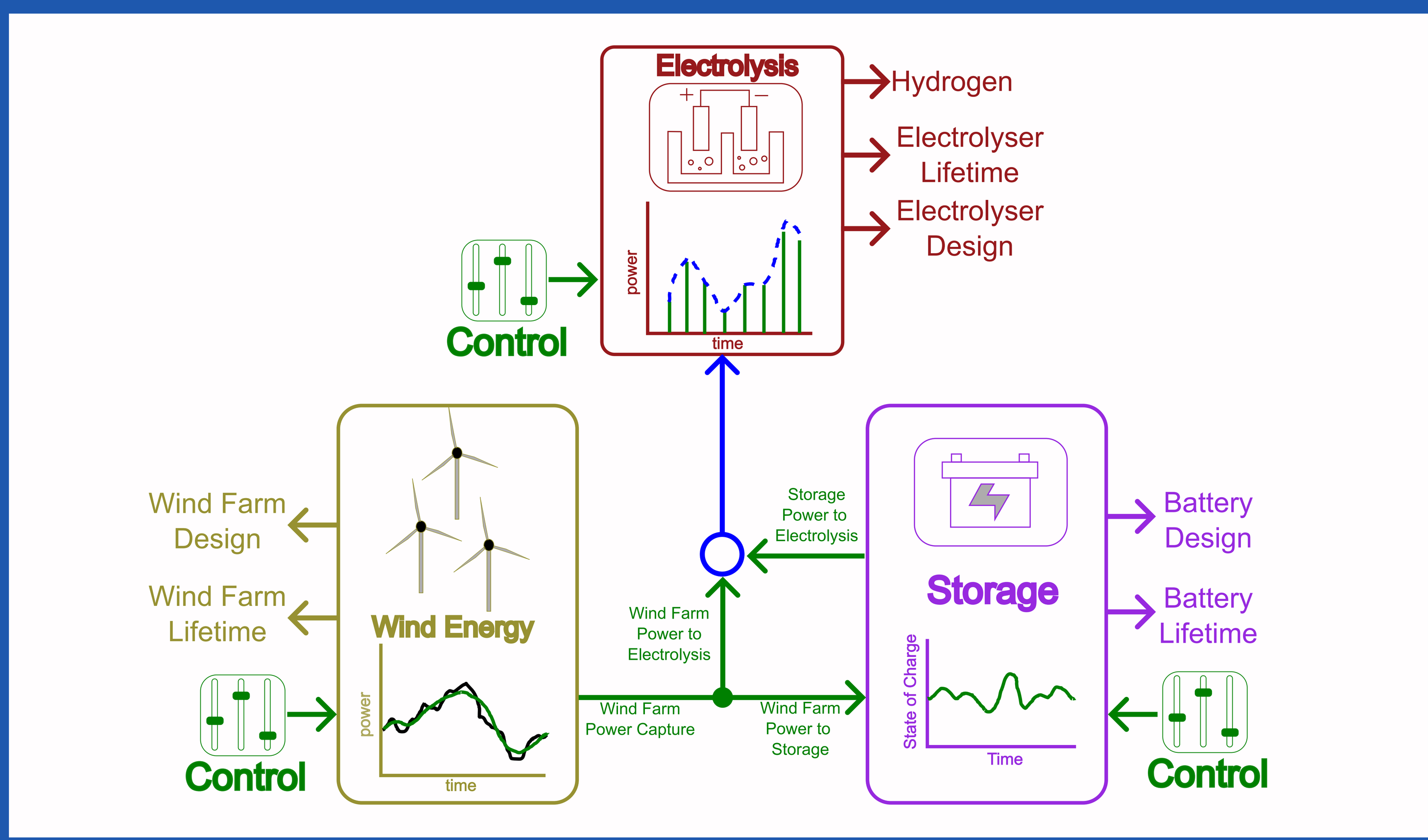


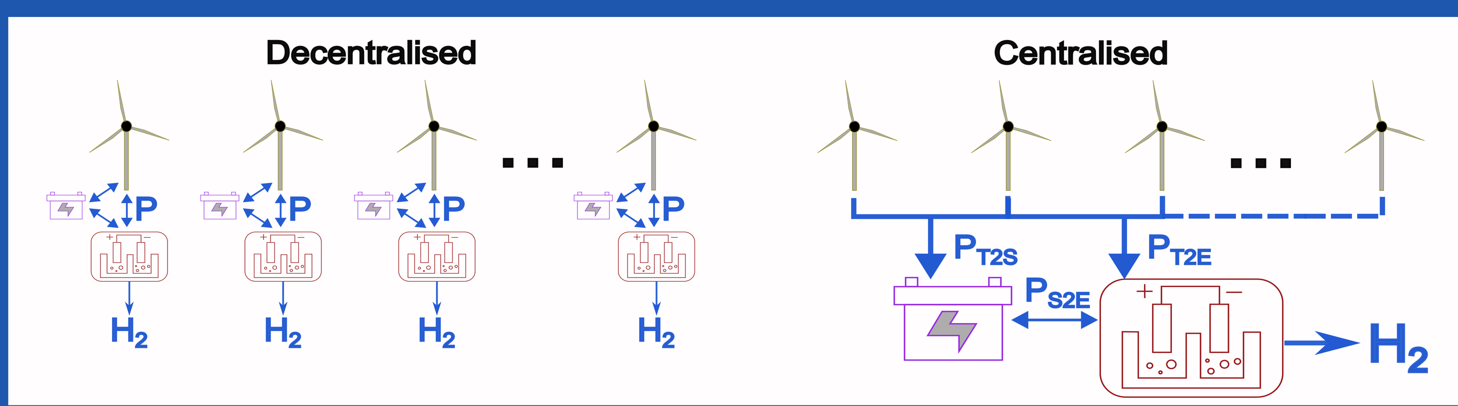
Stacks consist of cells connected in series, banks are represented as stacks in parallel, and electrolysers are represented as banks in parallel.

Degradation of Cells

Electrolysers' performance degrades over time due to mechanical and chemical wear mechanisms. In [2], these mechanisms were divided into three types: steady operation, fatigue loading and on/off cycling. An electrolyser with a similar design to that used in [2] was simulated connected to a single 5MW wind turbine.

The volume of hydrogen produced and the wear rate of the electrolyser matched adequately to the results presented in [2] once the difference in power input frequency was accounted for, verifying the model. Clear advantages of the model presented here are the ease with which electrolyser design can be altered, and the coupling of the model with the battery and wind farm components.



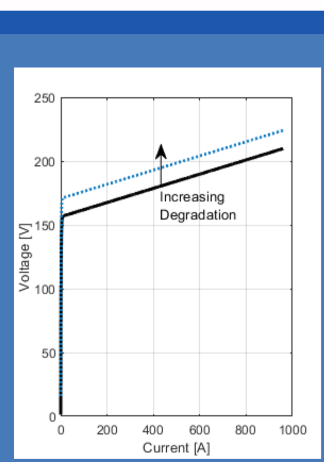


$$d = r_s c_s + r_f c_f + r_0 c_0$$

$$c_s = \int_0^{\tau} V_c(\tau) d\tau$$

$$c_f = \sum_{j=1}^{J} m_{R,j} n_{R,j}$$

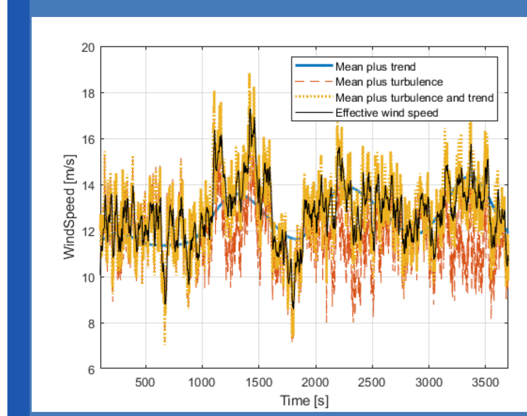
$$c_0 = n_{off}$$

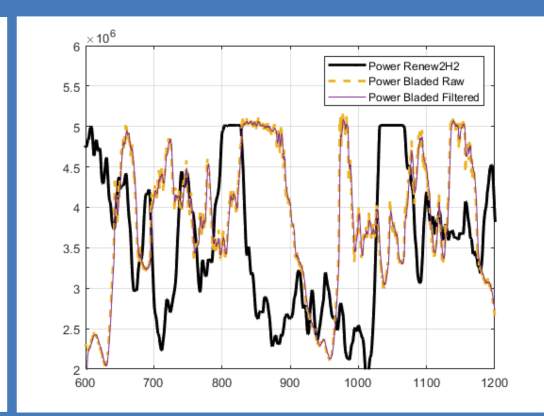


Wind Farm Modelling and Verification

The wind farm is modelled to provide representative power output from the farm at 1Hz for long periods of time (e.g. 1 year). To minimise computational effort, a simple power curve model of the wind turbine is used. When using a simple model such as this, **accurate modelling of the wind resource** is critical. 1Hz data for wind farms is sometimes available, but can have missing elements and is site specific. The approach taken here is to synthesize 1Hz effective wind speed data from readily available (e.g. from [3]) hourly average data.

A Gaussian process approach is used to "retrend" the wind data, based on the inverse of the detrending approach used in [4], to make the one hourly data vary realistically across the hour. Kaimal turbulence is added to include variation at higher frequencies, and care is taken to ensure that the data has no discontinuities. Finally, the method from [5] is used to convert the point wind speeds to effective wind speeds.





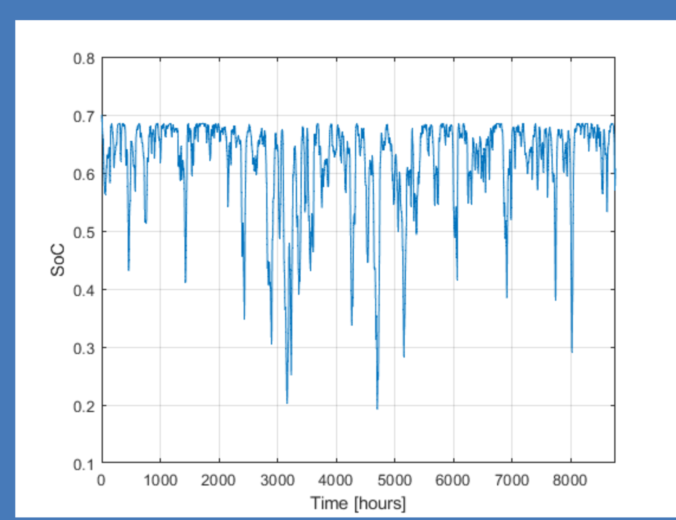
For wind farm simulations, the "trend" variation is currently independent for each turbine - work is ongoing to find typical coherence of "trend" variations to be added to the model. Wakes are not currently considered.

Control and Battery

The battery model is for an LMO battery and is based on that used in [6], itself based on work in [7], and includes calendar ageing and cycle ageing based on SoC and DoD.

The battery is used to smooth the power supplied to the electrolyser and to provide ancillary power to critical components when wind power is insufficient. The battery power flow control can be setup by the user. Here, the battery uses a proportional controller to keep close to the desired SoC, whilst inputting or outputting power as required to smooth the power flow. Large dips in SoC also occur when there is no wind power available, this highlights the potential advantage of mixed sources of energy.

Electrolysers are operated using a "hesitant on/off" method, whereby operational units (stacks, banks, or electrolysers depending upon the designer's choice) are kept in their current condition (on/off) unless the change in power supply requires change. Electrolysers with the least degradation are prioritised for on/off switches.



SoC of 50MWh battery - single turbine - 60s time constant

Impact on Plant Design

Early results using this model have highlighted some critical insights into design of off-grid wind to hydrogen systems.

1. A **centralised approach** is better for electrolyser life and hydrogen production for an equivalently specified electrolyser, turbine, and battery.
2. It is critically important to **model higher frequency variations in power supply** (sub-minute) for smaller wind farms.
3. **Control** can play a key role in optimising performance
4. **Spatial coherence** of the wind between turbines over **sub-ten-minute time scales** requires careful consideration and further research.

Due to the averaging of stochastic power variations across turbines, larger wind farms that adopt a centralised layout see reduced variations in power at higher frequencies, leading to longer electrolyser and battery lifetimes and smaller battery requirements. Whilst not an unexpected result, this model begins the process of quantifying the impacts, which appear to be significant. In simulations using similar electrolysers, controllers, and batteries, a centralised approach for a 6-turbine wind farm saw a increase in hydrogen production of 18% and a slight increase in battery lifetime. As these effects are due to turbulence and wind trends, medium to high frequency modelling of wind turbine power output is of critical importance.

Control plays a key role in enhancing electrolyser and battery lifetimes. The prioritisation of less degraded electrolysers for on/off events has a large effect on lifetime (as seen in [2]), however, especially for smaller wind farms, smoothing of the power flow is essential. For the single wind turbine case, smoothing of the power flow is required to achieve electrolyser operational lifetimes over one year. When a smoothing effect of a time constant of 60s is used, results are similar to [2], in which one minute average power flow was used. However, such a large smoothing effect puts considerable strain on the battery. Optimising the lifetimes and costs of these components through control of the three components of the system will be a focus of future work.

Finally, spatial coherence of the wind directly impacts the improvements in lifetime from a centralised approach. In the work here, Veers method is applied to the turbulence and the "trends" are modelled as uncorrelated. In reality some correlation will exist for some larger wind structures.

Work presented here is initial results and insights, however, the model developed is designed to investigate these areas further and, by the end of the current project in February 2026, be made available for others.

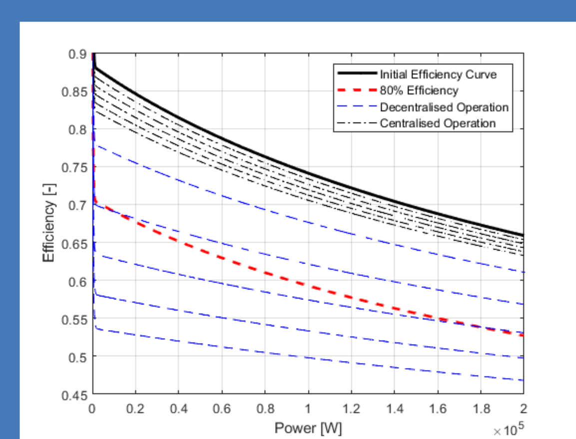
Key Result - Centralised vs Decentralised

A key early result is a comparison between decentralised and centralised operation. Using the same electrolyser topology, a single turbine coupled with a single electrolyser and battery is compared with 6 turbines connected to 6 electrolysers. Simulations are run for 5 simulation years.

The first figure compares electrolyser efficiency over each year for each case. [2] recommends replacing an electrolyser when the efficiency drops below 80% of the original curve, suggesting a vast difference in electrolyser lifetimes for the two approaches.

Hydrogen production is significantly higher in the centralised case, due to reduced electrolyser degradation, and battery lifetime is also slightly increased for identically sized batteries.

Battery life (time before the battery drops below 0 SoC in a simulation) is 54 months for the centralised case and 52 years in the decentralised case.



Battery Lifetime	
52 months	54 months
Decentralised	Centralised

Hydrogen Production*	
1391 t/year	1645 t/year
Decentralised	Centralised

*Averaged over 5 years - no electrolyser replacement

References

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