Recommendations for the Optimisation of Tidal to Hydrogen Systems

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FORWARD 2030

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Executive summary

Viable tidal stream energy resources are often situated around remote locations that may have limited and frequently disrupted grid connections. The slow speed of grid upgrades in these regions is a major barrier to the growth of the tidal stream sector. One proposed solution to this is the introduction of local offtake industrial users that can take advantage of the local generation of green electricity at advantageous pricing as part of a behind the meter power purchase agreement. For local businesses this replaces reliance on expensive retail electricity and heavily polluting diesel generators. This arrangement may also have the potential to attract new industries to these areas. The predictability of tidal stream energy can provide a clear advantage over other intermittent renewable generation technologies.

Although tidal generation is predictable, it is also cyclical, with daily cycles that create four periods of slack water every day, together with monthly and yearly cycles that mean there are large, predictable variations in the power generated. Battery storage has been proposed as a method to smooth this generation, thus providing continuous power to an offtake, but little information is available on how this would work in practice. Tidal power can also be subject to large instantaneous power variations.

The Fall of Warness tidal generation site off the island of Eday, Orkney, which is operated by the European Marine Energy Centre (EMEC), will become subject to constrained grid export as the number of tidal energy converters (TECs) on the site increases. In anticipation of this, EMEC has introduced a hydrogen production plant on its Caldale onshore site on Eday and has installed a vanadium flow battery (VFB) to replicate this challenge. A local wind turbine that can divert its generation during curtailment has also been introduced to the system to investigate whether the offtake could use this intermittent energy beneficially. At time of writing, this plant is not yet fully operational, but site acceptance data is available. This report uses this data, together with tidal stream current speeds at the TEC locations, to model how these could be used to optimise hydrogen production by:

- Maximising the operational time of the hydrogen electrolyser (HE) at the most efficient setpoint; and
- Minimising operations and maintenance costs both by reducing the quantity of startup cycles and using tidal cycles to schedule regular maintenance cycles.

This report shows how the predictability of tidal stream and curtailed wind energy can be combined with energy storage systems to maintain optimum hydrogen production rates for most of the time, with turndown to minimum at neap tides. The periods of lowest generation are approximately six months apart and offer an ideal opportunity for planned maintenance of both the electrolyser equipment and the TECs. The availability of a grid connection, even if limited, enables excess generation to be exported during spring tides and the import of grid electricity for the plant during times of low generation or TECs being unavailable. Full economic modelling can be used to establish the most beneficial operating profile for grid import, increased battery capacity or stopping production during the remaining periods of low generation, however this was beyond the scope of this work. The addition of the wind turbine was shown to have minimal benefit for the EMEC site as curtailed wind energy was limited, however, with careful system design, this benefit could be increased.

Tidal energy converters, combined with energy storage, can deliver stable, near continuous behind the meter electricity for industrial offtake industries. Early detailed modelling, based on local tidal resource and equipment specifications, is important during the design feasibility stage to enable careful sizing and specification to establish the optimal economic operating profile for each individual system.

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Abbreviations

Acronym	Full version with definition
ANM	Active network management - the Orkney ANM system uses real time network information to calculate safe levels of generation for managed connections in accordance with their commercial agreements
BESS	Battery energy storage system
CfD	Contract for Difference – scheme used by the UK government to incentivise investment in low-carbon electricity generation
DNO	Distribution network operator
EMEC	European Marine Energy Centre
ERE	Eday Renewable Energy – a private company that operates the community owned wind turbine on Eday
HE	Hydrogen electrolyser
kVA	Kilovolt-ampere
kW	Kilowatt
kWh	Kilowatt-hour
LIFO	Last-in, first-out – the prioritisation system used by the Orkney ANM
Li-ion	Lithium-ion battery – a battery technology that offers power density and cost advantages
MP3	Measurement point 3 - the measurement point on the Orkney ANM system that dictates whether curtailment will take place at Eday
MW	Megawatt
MWh	Megawatt-hour
O2	The Orbital O2 2 MW TEC that is currently onsite at the Fall of Warness and is used for this modelling
O2-X	The Orbital O2-X 2.4 MW TEC that is expected onsite at the Fall of Warness and is used for this modelling
OEE	Ocean Energy Europe
PEM	Proton exchange membrane – an electrolysis technology that is considered more suited to renewables due to its responsiveness
RMS	Root-mean-squared
SSEN	Scottish and Southern Electricity Networks
TEC	Tidal energy converter. Any device that extracts energy from tidal currents e.g. the Orbital O2
TWh/y	Terawatt-hours per year
SAF	Sustainable aviation fuel
UK	United Kingdom
VFB	Vanadium flow battery – a battery technology that offers life span, safety and scalability advantages
WP	Work package

Definitions

Phrase	Meaning
Caldale	The hydrogen production facility operated by EMEC that is located on the island of Eday
Curtailment	The reduction or limitation of electricity generation, often done to balance supply and demand, particularly when there is an oversupply of renewable energy
Fall of Warness	The grid connected tidal energy test site operated by EMEC, off the island of Eday. The subsea cables come ashore at Caldale, where the power can either be sent to the grid or to the hydrogen production facility.
Partially islanded	Contracts for Difference (CfD) in the UK refers to this as a generator that is connected to the electricity grid for only a portion of its output, while the remaining output is consumed on-site or by a private network
Turndown	The operational range of a device, specifically the ratio of its maximum capacity to its minimum capacity.

1 Introduction

1.1 FORWARD2030

Ensuring the European energy transition meets net zero targets by 2050 requires securing significant investment and public support of low-carbon renewable energy generation. Tidal stream energy is an emerging sector that utilises the predictability of tides to deliver a reliable power supply with a low carbon footprint due to the energy density of water and close proximity to coastlines. Ocean Energy Europe (OEE) reports for 2024 state that almost 32 MW of capacity have been deployed in Europe since 2010, of which 12.7 MW was operational in the water in 2024 (OEE, 2025). Capacity additions are expected to increase rapidly in 2026-2027 as pre-commercial farms are deployed with a mix of public funding and private-sector equity / project debt financing. European countries now foresee the deployment of 670 MW of ocean energy by 2030, although OEE reports there is still a capability to reach 1 GW by 2030 if national governments increase support and raise their targets (OEE, 2025). OEE's 2030 Ocean Energy Vision that was developed in 2020, presents high and low growth scenarios for the tidal stream sector to 2030, with a high-growth projection of 2,388 MW installed capacity by 2030 with cost reductions to around €90 MWh-1 (OEE, 2020).

In line with the vision's high-growth scenario, the European Union Horizon 2020 FORWARD2030 (Fast-tracking Offshore Renewable Energy with Advanced Research to Deploy 2030 MW of tidal energy before 2030) project has been established to deliver a series of high-impact cost reductions to achieve a breakthrough 2030 MW of tidal stream deployment by 2030. Led by Scottish-based tidal energy technology developer Orbital Marine Power, the project partnership consists of SKF GMBH and SKF SVERIGE AB (major global manufacturer with over 100 years' experience in rotating machinery), LABORELEC (research institution of ENGIE, the third largest electrical utility in the world), University of Edinburgh and University College Cork (globally renowned experts in techno and socioeconomic analysis and marine spatial planning), and the European Marine Energy Centre (world leading marine energy demonstration centre and internationally accredited test laboratory). Orbital Marine Power has pioneered innovative floating tidal technology since the company's inception in 2002. Refinement and optimisation of the company's previous SR2000 device, then cited as the world's most powerful tidal turbine, has led to the current twin 20 m rotor, 2 MW O2 design. FORWARD2030 will support continued innovation on Orbital's forthcoming O2.X technology design, to further reduce LCOE of the technology by 25%.

Recent practical resource estimates indicate that tidal stream energy could contribute 11% (34 TWh/y) to the UK energy mix by 2050 (Coles et al., 2021). Practical resource defines the annual yield potential using tidal stream technology, after economic, environmental, regulatory and social constraints have been applied. As the tidal sector progresses from single device and small-scale array demonstrations to larger scale arrays in support of decarbonisation targets, it is crucial to understand and solve these constraints to maximise practical tidal stream energy exploitation.

One of the challenges (particularly evident at the EMEC site) to the ambitious timescales being targeted in FORWARD2030 for the deployment of large-scale tidal energy arrays is the lack of availability of electricity grid connection capacity in remote locations with good tidal resource. Under Work Package 6 (WP6 Energy Management and Array) of this project, the optimisation of the offshore energy system to the local grid using energy storage systems and the onsite hydrogen electrolyser (HE) is investigated.

This report explores how to optimise utilisation of the energy generated by the tidal generators in a behind the meter system that incorporates a local offtake, in this case green hydrogen production, and an energy storage system to maximise utilisation of the electrolyser. This model is then further extended to investigate the effect of diverting power to the islanded system from a local wind turbine when it is subject to curtailment.

The findings from the model are then qualitatively assessed to understand how they may be extended to larger tidal farms and how these may be integrated with wind farms. The work is then extended to examine how this may affect potential offtake industries, including synthetic fuel production.

1.2 Tidal and industrial offtake

Viable tidal stream energy resources are often situated around remote locations that may have limited and frequently constrained grid connections. This constraint on the availability of electricity, and increasing cost of retail electricity, has a further impact on local industries by increasing costs and restricting growth. The predictability of tidal stream energy can provide an economic growth opportunity to attract new industries in a way that other intermittent renewable sources cannot.

To do this, partially islanded systems can be introduced, which are supported in the UK as part of the Contracts for Difference (CfD) scheme. These enable a private network to supply power to an off taker using a behind the meter arrangement, with surplus power being supplied to the grid. This local offtake option enables the generation to be higher than the local grid would have been able to handle. It may also provide an opportunity for distribution and transmission grid balancing services if the offtake opportunity is large enough.

To implement this system for tidal, it is important to undertake a detailed analysis to understand:

- What tidal generation will look like for a typical annual cycle;
- How batteries may be used to ensure consistency of supply; and
- How operation of a partially islanded system can maximise a limited grid connection.

To understand how the process would look in practice, this deliverable undertook the above analysis for the tidal energy converters (TECs) located at the Fall of Warness tidal site and its associated Caldale hydrogen production plant.

1.3 The Caldale facility

The Orbital O2 is located at the Fall of Warness tidal site and the Orbital O2-X will be deployed at this location. These will provide power alongside other TECs, with the subsea cables coming ashore at EMEC's substation located at the Caldale site. This site has the following grid connections:

- 4 MW unconstrained connection
- 3.2 MW subject to active network management

The local Orkney grid has a surplus of renewable generation and to manage this during times of excess generation, a local active network management (ANM) system has been implemented.

The potential for curtailment of generators connected at the Fall of Warness was identified before 2015. To mitigate this, a hydrogen electrolyser and the associated plant was installed at the EMEC Caldale facility as part of the Surf ‘n’ Turf project[1]. This produced the world’s first green hydrogen made using electricity generated from tidal energy in 2017. Eday’s community wind turbine, owned by Eday Renewable Energy Ltd (ERE), can also divert its curtailed generation to the electrolyser when there is no generation from the TECs. In 2021 a vanadium flow battery (VFB) was added to the electrolyser plant to investigate how it would improve the uptime of the electrolyser. A Li-ion battery is intended to be added to this system as part of the FORWARD 2030 project, to give an energy storage solution on the grid side of the network.

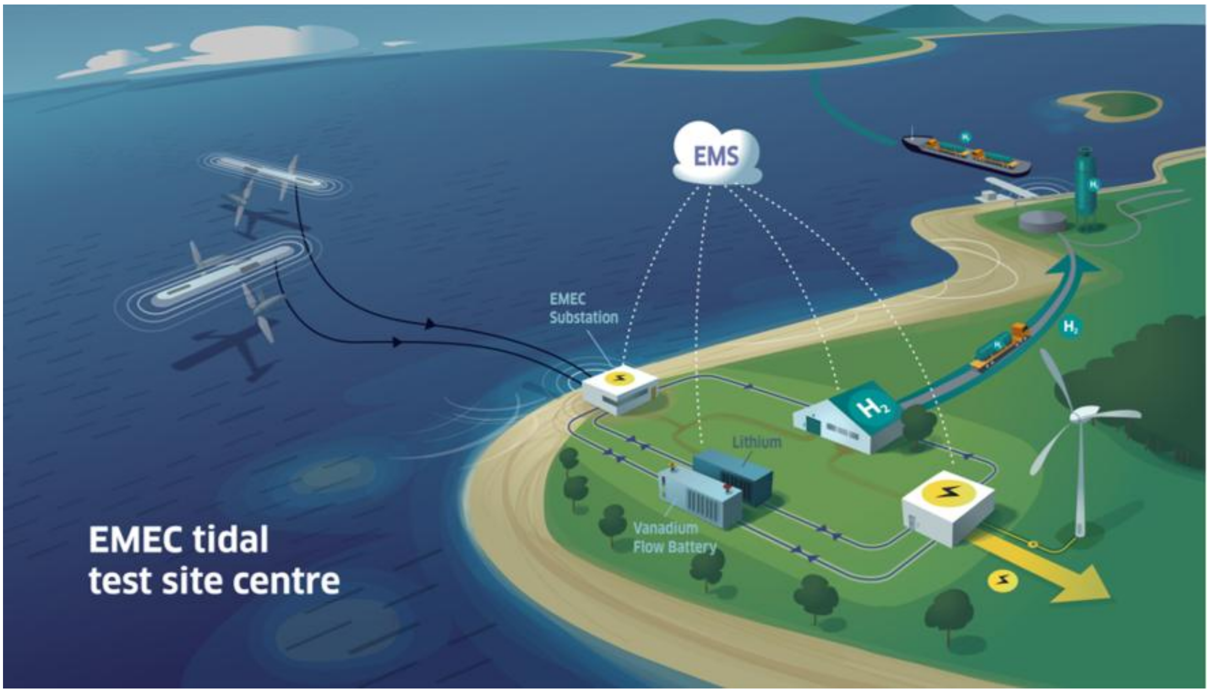

Figure 1 | Simplified graphic of EMEC’s Caldale facility including the hydrogen production facility

The network at the Caldale site is set up as a partially islanded network. This means that the various generators that come to site can be metered and the developers paid for the energy that they produce. In addition, it allows the electricity generated by the TECs to be used to power the hydrogen electrolyser and/or the vanadium flow battery in a behind the meter arrangement. Due to connection agreements with the electricity distribution network operator, the VFB, curtailed ERE wind turbine connection and the electrolyser are on a closed network that cannot export to the grid: this is due to the restrictions required by the ANM scheme. The Li-ion battery is intended to be able to export to the grid and therefore is located before the closed section of the network.

The most efficient operation of the electrolyser is achieved when the electrolyser is run continuously at between its nominal operating point of 35% and 65% of the electrolyser’s nameplate capacity. Above 65%, the efficiency achieved is lower and degradation of parts of the electrolyser is accelerated, thus increasing maintenance costs.

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[1] https://www.surfnturf.org.uk/

This model investigated:

- **The detailed generation of each TEC**: based on its location and approximate power curve, through a yearlong period.
- **The Li-ion battery to manage sub-second variations:** thus maximising grid export.
- **Whether a protocol can be developed to allow the VFB and electrolyser to be operated** in a cohesive manner to both avoid curtailment and maintain operation of the electrolyser through a full year of tidal cycles.
- **The duration of times when the electrolyser cannot be provided with behind the meter power** due to seasonal neap tides in comparison to maintenance cycles. In this way preventative maintenance can be scheduled to coincide with tidal cycles.
- **How curtailed electricity from the ERE wind turbine** can be used by the electrolyser and VFB and how much benefit this provides.

The potential for grid balancing services were then also investigated. Finally, this work was then extended out to investigate how it may be extrapolated to the requirement for other offtake opportunities.

2 Modelling

A model of the energy flows at EMEC has been developed to investigate enhanced logic for the optimal allocation of power to various components such as the VFB, Li-ion battery, grid offtake and the hydrogen electrolyser. It is based upon previous work to establish a forecast of generation for the site. The model itself is custom code, written in Python, and is designed to be configurable based upon JavaScript object notation (JSON) files. These files define:

- Time periods to be simulated;
- TEC/generation details (power curves, thresholds);
- Resource input (e.g. hydrodynamic or wind time series);
- Wiring of the site (connectivity between energy budgets);
- Site export arrangements and limits;
- Active network management time series;
- Storage: rate limits and energy stored; and
- Alternative offtake limits (power sinks).

The model itself operates on a one second time interval and maintains its internal data model between successive time steps to produce a forecast of the parameters for each system component modelled. In this sense, it is purely deterministic. A random factor was included against TEC generation to allow for an analysis of the effect of sub-second variation. Input time series are interpolated to one second intervals from their source temporal resolution.

Other details of the modelling include:

- The internal data model is implemented in-memory as a Python dictionary;
- Input files are typically taken in comma separated value format with dates and times based on UTC as defined in the international standard ISO 8601;
- Hydrodynamic input is provided from depth-averaged tidal predictions interpolated at TEC locations from EMEC's hydrodynamic model, built upon DHI MIKE 21 Flow Model FM, using DHI's Global Tide Database (GTD) for forcing;
- Output files are written as Python pickle files (.pkl) for performance reasons; and
- The Python library Matplotlib is used to produce plots from these output files using a set of secondary scripts.

The following sections discuss the modelling of each component in greater detail. The model is set to predict power generation between 1 June 2026 and 31 May 2027. All results referred to in the following work are the simulations generated by the model during this period.

2.1 Grid connections

The current export capacity of the Fall of Warness tidal test facility is:

- 4 MW connection, unconstrained, not subject to ANM
- 3.2 MW managed connection, subject to ANM

Because curtailment is seasonal, a full-year cycle must be considered when modelling the ANM. Curtailment is applied based on half hourly Orkney ANM data provided by SSEN covering the period 2018 to 2021, inclusive. 2018 ANM data is used for 2026, and 2019 is used for 2027, thus avoiding any impact from the COVID lockdowns of 2020-2021.

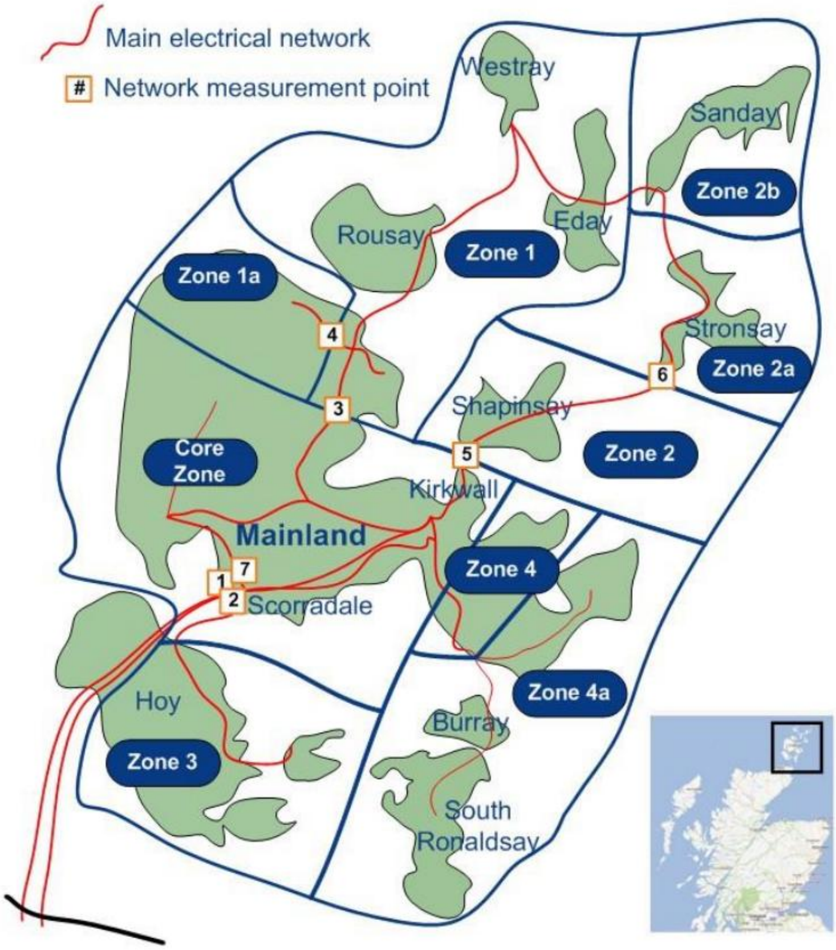

Figure 2 | Diagram showing the zones and measurement points of the Orkney ANM

The Fall of Warness is located in zone 1 and curtailment is dictated by measurement point 3 (MP3), as shown in Figure 2. This operates on a last-in first-out (LIFO) basis and can either curtail or stop generation. For site modelling of the 3.2 MW connection, the ANM signal is a continuous signal, representing an overhead of remaining export available of the ANM trim level. The 3.2 MW output is then reduced to fit within the remaining overhead. The 3.2 MW connection is position 28 in the queue and this is the position that EMEC has curtailment data for and so is used for all ANM modelling in this piece of work.

2.2 Generators within the EMEC model

2.2.1 Tidal energy converters

Within this model, 10-minute time series of tidal stream current speed at known TEC locations is used, along with approximate cubic TEC power curves to provide instantaneous power at one second intervals.

All TEC information utilised has been kept confidential and is based on approximations. All TECs are assumed to be on-site for the duration of the simulation period.

TECs are known to have spiky output, which is not constrained by their nameplate generation. Random fluctuations based on sensible approximations are applied to the TECs in the model, on a one second interval, but there is no temporal aspect to this. The distribution of these random variations is taken to be rectangular for the purposes of modelling – i.e. the adjustment is a random number selected within the range of ±N% of instantaneous power output, depending on the TEC.

2.2.2 Wind turbine

A synthetic time series for the Eday Renewable Energy (ERE) wind turbine is generated. EMEC has an agreement with ERE, whereby when wind generation is curtailed, the EMEC hydrogen and VFB sub-systems can be switched to receive energy from the ERE wind turbine. As this is a toggle switch, in practice it would only be applied when the TECs are not generating. The wind speed input to the model for the ERE wind turbine is set to zero when normal operations apply. This means that a value for wind is only applied to the model when curtailment is expected to take effect.

ANM is applied seasonally. The 2018 and 2019 data for MP3 is used with 95% threshold (a figure established from proprietary EMEC studies) to set wind speed to zero for the input timeseries used for the ERE wind turbine. This has the effect of forcing the output power for the ERE wind turbine to zero, unless curtailment is being applied.

Surface (10 m) wind speed is taken at hourly intervals for the point 2.815 ° W, 59.148 ° N, using the E.U. Copernicus Marine Service Information (2025), dataset “Global Ocean Hourly Reprocessed Sea Surface Wind and Stress from Scatterometer and Model”, which is at 0.125 ° resolution.

The ERE wind turbine is above the Fall of Warness 3.2 MW connection on the ANM LIFO system, hence it will be subject to less curtailment as it is position 12 as opposed to the position 28 of the EMEC tidal site. However, the position 28 information provided by SSEN has been used in this exercise as no other information is available. It should result in greater curtailment and an overestimate of power from the ERE wind turbine into the EMEC system.

The ERE wind turbine is an Enercon E44, with power curve details taken from wind-turbine-models.com (2025). The power curve is applied using trapezoidal averaging against mean wind speed. Temporal trapezoid averaging is also used to obtain an instantaneous value of mean wind speed at one second resolution, which works well between points of successive output. However, there will be issues when curtailment begins and ends, since this averaging method will lead to a linear hourly increase from, or decrease to, zero. This is different to how the curtailment would behave in reality as the curtailment will apply instantaneously as an ANM signal is received.

No random fluctuations are applied to the ERE wind turbine power output. This is primarily because estimation of this is beyond the scope of the present study. This approach is justified as:

- Turbulence effects should not influence wind turbine output power significantly. These occur on a much finer spatial scale than the Enercon E44 rotor, which is 44 m in diameter.
- Gusts are difficult to estimate. Some studies suggest a roughly ±20% relationship between a wind turbine output power and a range of observed instantaneous wind speed (Bandi and Apt, 2016). While these will cause fluctuations in rotor speed and hence power output, an accurate representation of this is hard to establish, however, it will be normally distributed around the mean wind speed, so in effect cancels itself out over time.
- The Enercon E44 is synchronous with the grid. This means that in normal operations the grid is expected to stabilise power output and physical speed changes by the rotor.

These factors justify that the model does not consider instantaneous power output fluctuations for the ERE wind turbine.

2.3 Modelling of generators and grid connections

The first stage of the model was run with just the generators and grid connections, including the effects of ANM. This enabled the first stage of the model to be proven whilst providing a baseline. Because curtailment is seasonal, a full-year cycle must be considered. A full year of output can be summarised as daily maximum power. From this, the limited scale of the potentially available curtailed ERE wind turbine contribution can be seen in Figure 3.

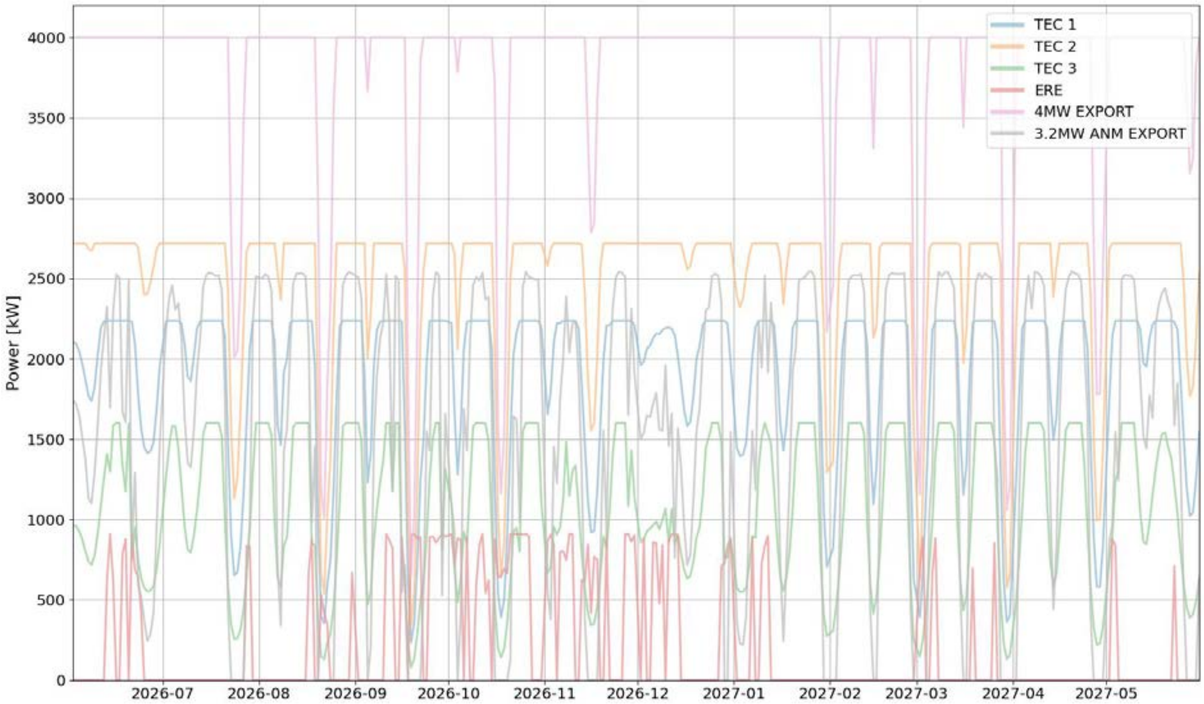

Figure 3 | Generator and site daily maximum export power [kW] June 2026 – May 2027

This work was then used to estimate the expected monthly total curtailment for tidal generation, as shown in Table 1. The total amount of energy expected to be curtailed for the 12-month period modelled is 229.6 MWh.

Month	Jun 2026	Jul 2026	Aug 2026	Sep 2026	Oct 2026	Nov 2026
Site Curtailment **[MWh]**	9.5	20.6	5.3	12.8	17.1	4.2
Month	**Dec 2026**	**Jan 2027**	**Feb 2027**	**Mar 2027**	**Apr 2027**	**May 2027**
Site Curtailment **[MWh]**	0.0	31.3	43.4	39.2	25.7	20.3

Table 1 | Energy expected to be curtailed for the EMEC site June 2026 – May 2027

2.4 EMS logic implementation

The model was then extended to:

- Build in the different battery energy storage systems;
- Allow for non-grid offtakes, in this case the hydrogen electrolyser. These may require a "keep-alive" power draw and may optionally have an optimum power level; and
- Allow for wiring between budgets, and therefore budgets without an offtake.

A representation of how the model was implemented is shown in Figure 4. This shows the various inputs used and how information passed through the model to generate the various outputs.

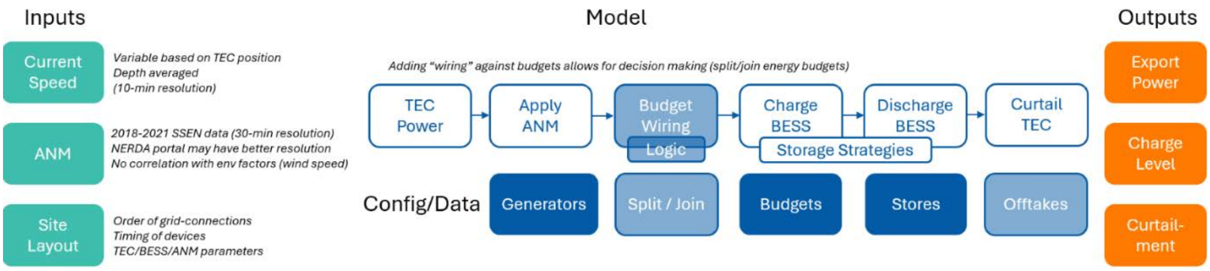

Figure 4 | A representation of the EMEC model including the inputs and outputs

The layout of the site was then applied to develop a logical schematic, as shown in Figure 5. Split/join points were allocated as decision points within the energy flow, with these being used to combine or divert power to or from different generator, storage or offtake budgets.

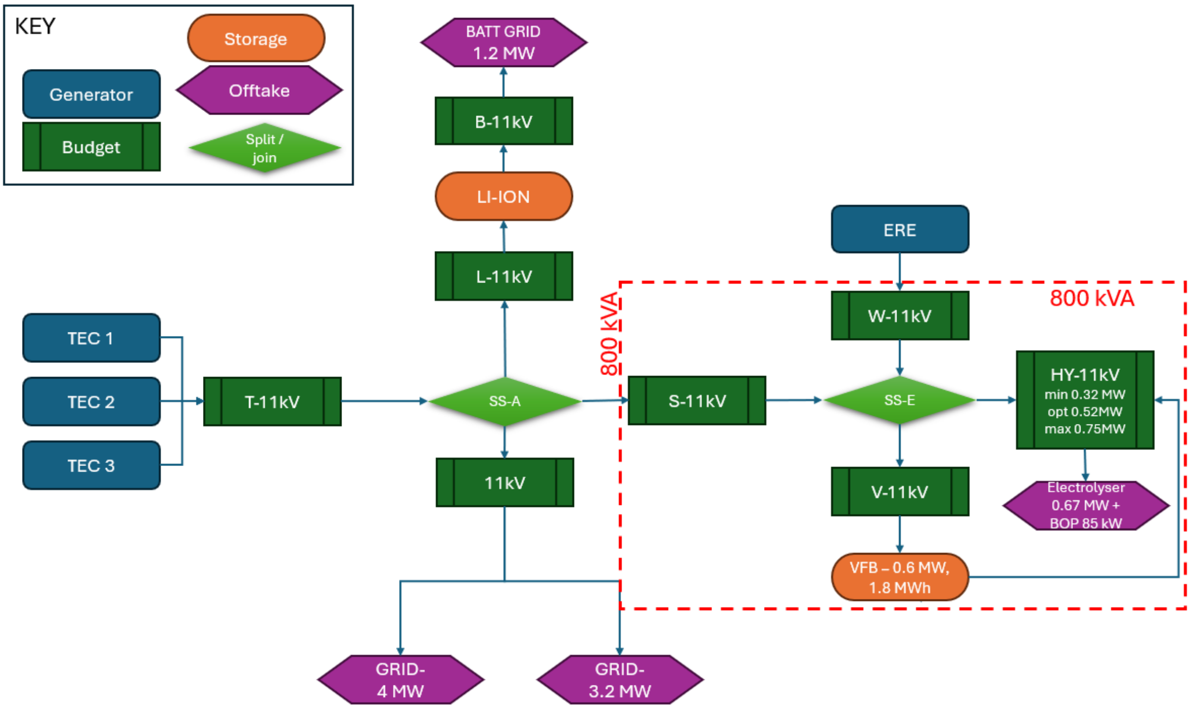

Figure 5 | Logical "wiring" of model components to satisfy Forward 2030 scenarios

The model was then split into distinct budgets and (compound) logical computation steps applied to:

- Divert power to the Li-ion battery for grid smoothing;
- Switch between tidal power and wind power (accounting for curtailment);
- Control the battery charge/discharge status; and
- Control power to the electrolyser, with a focus on achieving continuous operation in the range between minimal and optimum production rates.

Parameters can be varied to apply different scenarios or strategies to achieve optimal site operations. These have been defined as:

- Minimisation of curtailed energy to grid from generators on-site;
- Maximum consumption of ERE wind turbine curtailed energy (equivalent to "minimisation of curtailed energy", but is a specific case for the inbound ERE wind turbine power, which is only available when ERE wind turbine is curtailed);
- Maximum production of hydrogen at optimal efficiency (which requires continuous operation of the electrolyser and optimisation for an agreed power level as far as practicable); and
- Minimisation of fluctuating export power levels.

2.5 Battery strategies

There are two batteries built into the model. The VFB is currently installed on site and forms part of the closed network with the electrolyser. This cannot output to the grid as part of normal operation.

The Li-ion battery is intended to be brought to site as part of the Forward 2030 project. As the main consideration for the selection of this technology was to maximise export to the grid from the TECs, as detailed in Deliverable 6.1 (Laborelec, 2023), it is to be placed in a position on the EMEC network that potentially allows grid export to take place, but this means that it cannot export to the HE. For power to be provided from the Li-ion battery to the HE subsystem, the Li-ion battery discharge power would need to go through the 800kVA transformer. During periods of high tidal flow, the HE subsystem will be powered by TEC output power (to avoid grid constraint). This means that the Li-ion discharge power would compete with the TEC output power for a share of the 800kVA limit. If curtailed wind is available, and is chosen over tidal power, then the EMEC site layout currently means that the Li-ion battery would be physically disconnected from the HE subsystem.

In this way, the two batteries perform different functions with distinct outputs. The specifications for the batteries are:

- VFB: 1760 kWh, 600 kW max charge/discharge rate, with 74% efficiency overall.
- Li-ion: 1000 kWh, 1200 kW max charge/discharge rate. No efficiency rate was specified, so 100% efficiency is assumed.

No consideration has been given to battery degradation over time, or efficiency variations based on charge level.

2.5.1 Site output considerations

TEC power can be diverted directly to the hydrogen electrolyser. A full system output with a simple charging strategy over a day period is shown in Figure 6, including the various power levels against each site export contract.

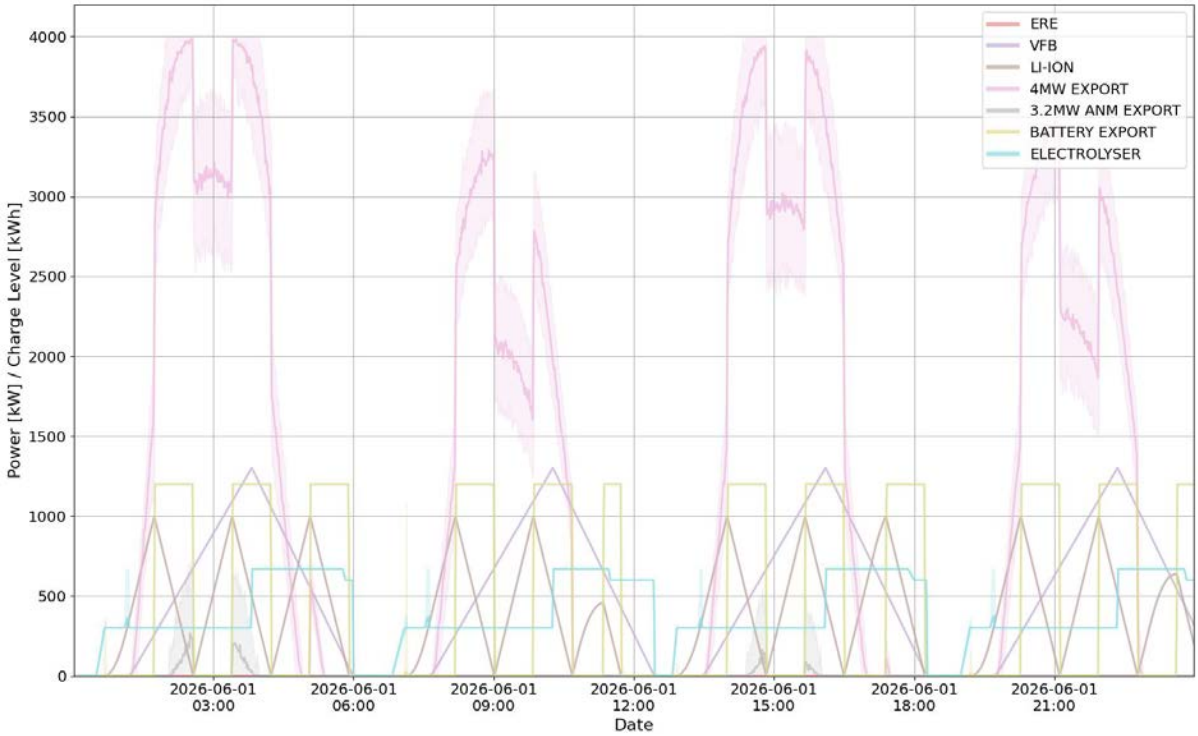

Figure 6 | Full site output, with TECs powering both VFB and HE, with VFB also discharging to HE

In the scenario, the overall site output jumps as the Li-ion switches between charging and discharging states. This occurs because less power is available for export while the Li-ion battery is charging, and when it discharges, it cannot also be charged. The Li-ion battery has its own managed connection contract and so can discharge at the same time as the other export contracts, if it is not subject to curtailment. The net result is that the site export power jumps by double the charge rate of the Li-ion when it switches mode:

- Half of this increase is from the discharge rate of the Li-ion battery; and
- The other half is the increase caused by the Li-ion battery no longer using power to charge.

In this case, because the battery system is assumed to be symmetric, this is a potential change in overall site export (when all grid-connections are considered) of 2.4 MW, which is significant for the site, even in the absence of any active network management.

3 Electrolyser power optimisation

This modelling has focussed on maintaining continuous operation of the electrolyser using only TEC generation by optimising the use of the VFB throughout the neap and spring tidal cycles. By operating continuously, the proton exchange membrane (PEM) electrolyser:

- Maintains efficient hydrogen production;
- Has a high operational time, thus contributing to a higher capacity factor;
- Suffers reduced degradation that can be caused by frequent start-stop cycles;
- Avoids venting and inefficient operation during starting and stopping;
- Can respond quickly to load fluctuations; and
- Can act as a sink for excess energy, either from renewables or grid balancing services.

The target setpoint of the electrolyser is 65% for this modelling. Above this the system efficiency reduces and the rate of degradation of the stack increases. The setpoint can also be reduced as far as the minimum turndown of 35%. Below this the electrolyser must stop producing hydrogen and be placed in standby, due to reduced hydrogen purity and increased risks. It is possible to operate the electrolyser at its nameplate capacity of 670 kW; however, this reduces efficiencies and the lifetime of the stack and is not recommended for long term operation unless there are very specific economic advantages for this. Finally, the introduction of curtailed wind energy from the local wind turbine shows how the system may be used as a sink for excess energy.

This operating profile would be expected to reduce the levelised cost of hydrogen, although this modelling would need to be extended to include detailed economic modelling to confirm this, as green hydrogen production will always be sensitive to electricity costs.

3.1 The electrolyser and VFB system

The diagram in Figure 7 shows how the TECs, electrolyser and VFB are connected, including the two 800 kVA transformers and the mechanism for switching from tidal to wind power. The 800 kVA limit means that if minimum power of 300 kW to the HE is supplied by the TECs, then 500 kW is available to charge the VFB, which is below its maximum rate. The next stage of the modelling investigated increasing the charge to the HE towards its optimum power, and correspondingly reducing the VFB charge, to investigate whether this could still achieve a charge that maintains hydrogen production through slack water until the TECs start generating again.

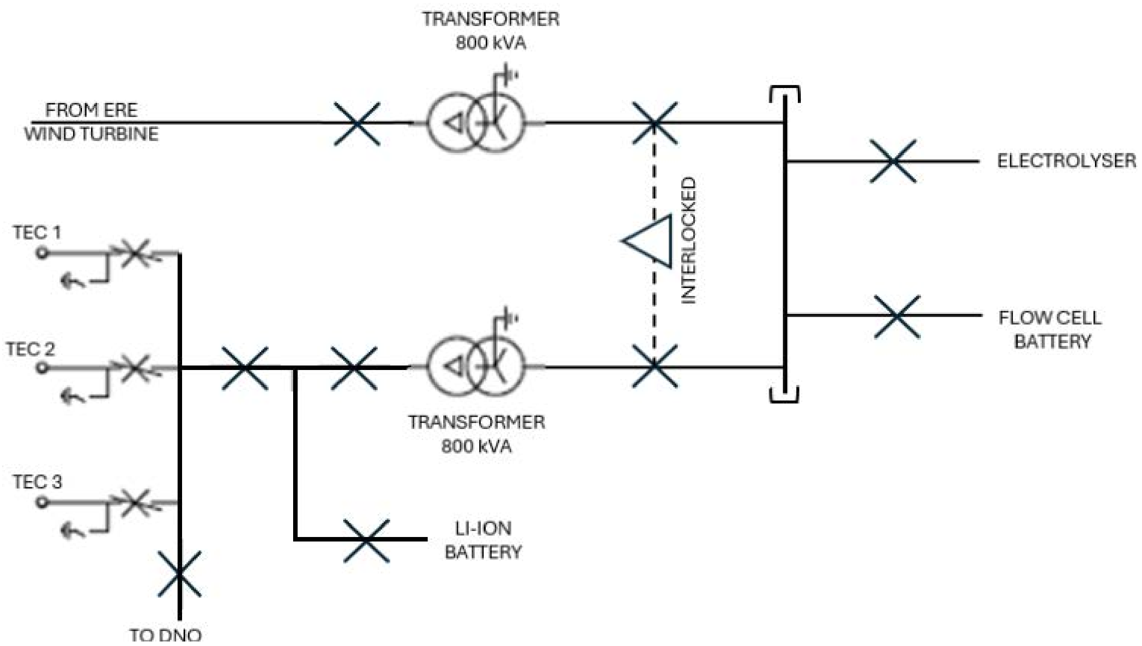

Figure 7 | Diagram showing how TECs, electrolyser and VFB are connected

3.2 Exploratory analysis of VFB charge/discharge rates

As an exploratory activity, the VFB was first set to charge and discharge symmetrically at a rate of 300 kW. The charging strategy for the VFB was set so that it charges when tidal power exceeds 300 kW, and only discharges when tidal power is below 300 kW. The result of this is shown in Figure 8.

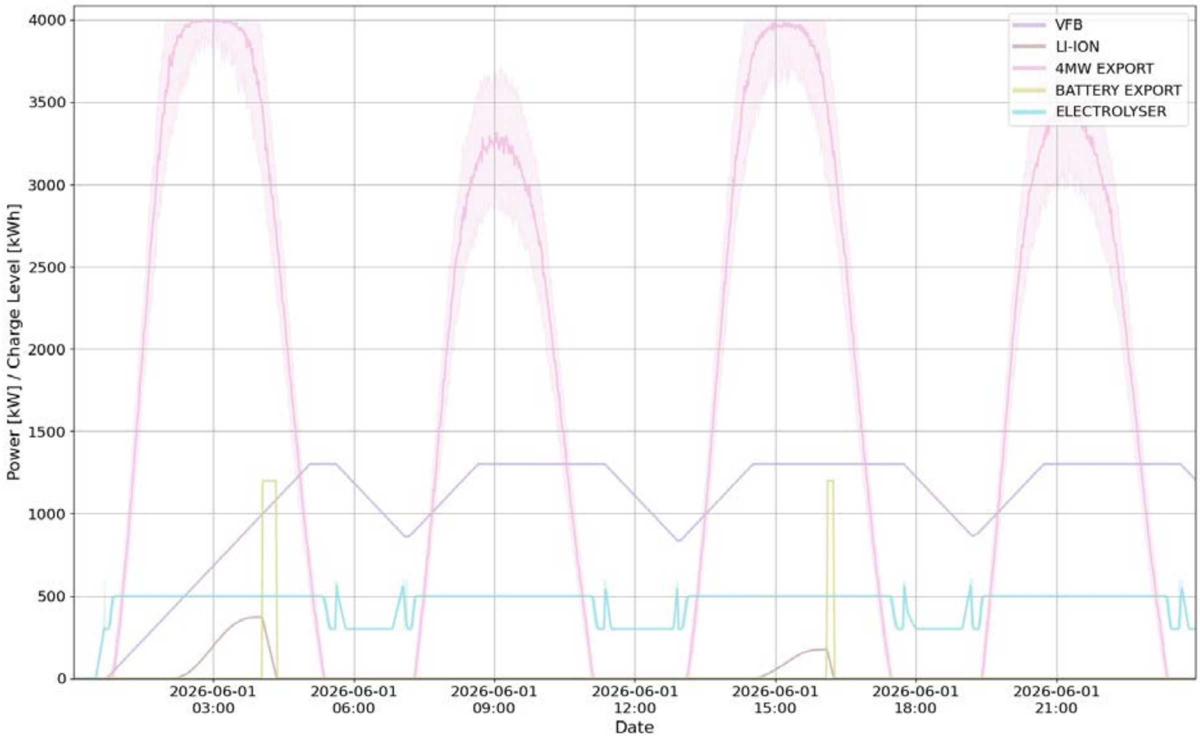

Figure 8 | Site / electrolyser output with symmetric 300 kW VFB charge/discharge rate

It can be seen that the HE now achieves 500 kW during the tidal period, which is the remainder of the 800 kVA limit. Minimum power is maintained across the slack period between tides, with peaks seen as the TEC generation drops below 300 kW and is combined with the VFB 300 kW output, but TEC generation falls away quickly to give just the 300 kW from the VFB.

3.3 Neap-tide sensitivity study

A sensitivity study was then undertaken on the behaviour of the system during neap periods for varying levels of VFB charge and discharge rates. The aim of this was to identify the optimum charge and discharge rate of the VFB for these time periods of lower energy generation. To achieve this, the neap tidal period with minimum power output for the modelling period of June 2026 to May 2027 was found: this was identified as October 2026.

The sensitivity analysis was then conducted by separately varying the charge rate and the discharge rate in increments of 100 kW and establishing the number of days where more than 300 kW of power was continuously supplied to the HE for each scenario. It is worth noting that discharge rates < 300 kW will, in general, not achieve the required minimum power during slack periods, so these were not evaluated. The results of this analysis are shown in Table 2.

# days HE>300 kW	Discharge rate [kW]			
Charge rate [kW]	300	400	500	600
100	22.9	26.6	25.6	24.9
200	22.6	27.6	27.2	26.8
300	22.2	27.5	27.2	27.0
400	21.7	27.1	26.9	26.7
500	2.1	7.6	7.4	7.2

Table 2 | Time in days during October 2026 where minimum HE power would be achieved for varying levels of VFB charge and discharge rate.

This analysis suggests a sweet spot between 200 kW and 300 kW charge rate, and 400 kW to 500 kW discharge rate. As the optimum HE power is around 520 kW, and considering the 800 kVA limit on-site, selecting 280 kW for the VFB charge rate will allow 520 kW to be provided by the TECs to the HE during tidal periods, when power is available.

Successive runs of discharge rate between 300 kW and 500 kW were then undertaken to try and establish an optimum discharge rate. The results of this can be seen in Figure 9. The main plot is the result of all the discharge rates overlaid on top of each other, with the thumbnails showing the plot for individual discharge rates.

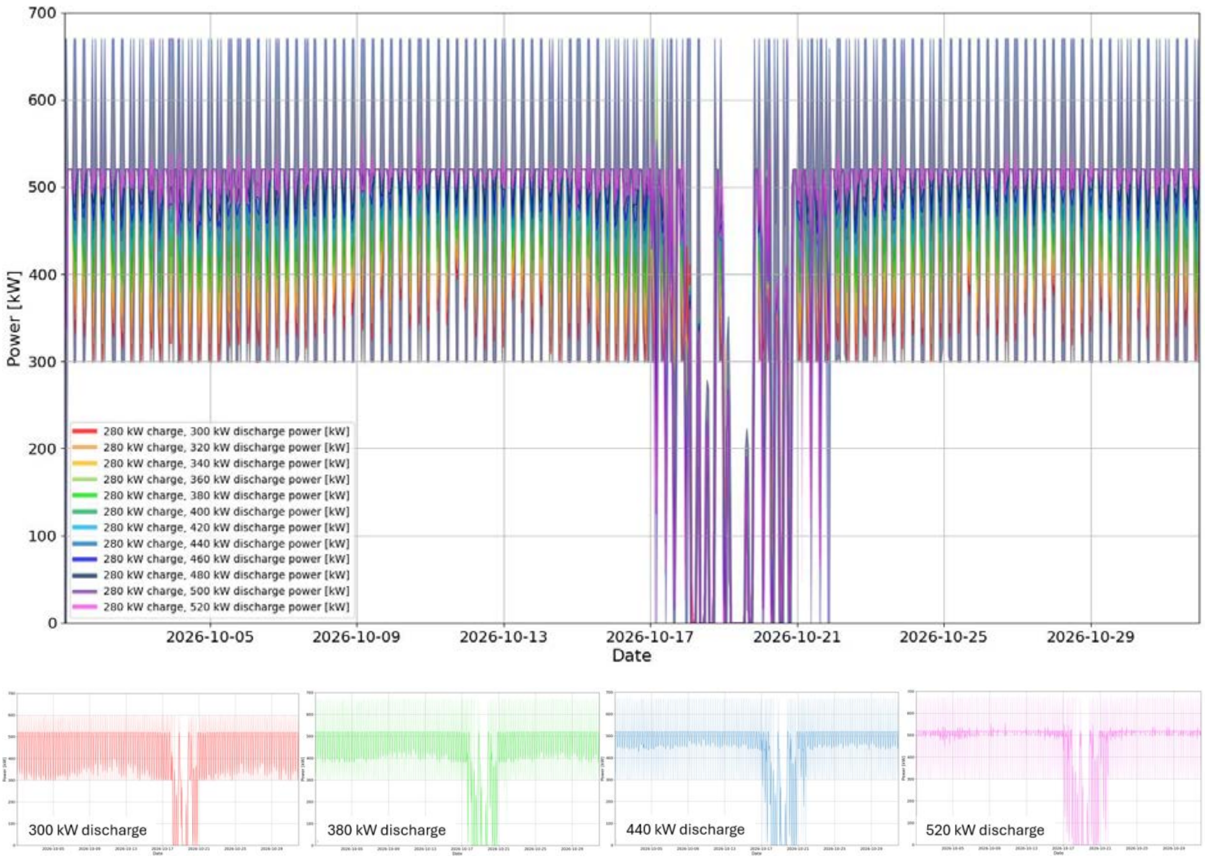

Figure 9 | HE power [kW] - VFB discharge rate sensitivity (300 kW – 460 kW)

As the discharge rate increases, the average power of the HE tends towards the optimum 520 kW. This is further borne out by considering the duration of the maximum neap period for each discharge rate, with this being defined as the length of time that the electrolyser power first dips below 300 kW to when it can achieve continuous generation again. The result of this is shown in Figure 10 (i) which shows that as the discharge rate increases, the duration of the period when the HE minimum power is not achieved also increases, with this tending from just under three days at minimum discharge rate of 300 kW towards just less than five days.

It should be noted that the minimum 300 kW is the lowest power at which the electrolyser can operate safely and produce hydrogen of the correct purity: below this power it must stop production and be put into stand-by. Even at this minimum 300 kW discharge rate, an outage would be needed during peak neap tides.

The HE could be operated intermittently during this time, however, there are longer 6-month and annual maintenance inspections that must be conducted on the equipment and require at least five days. Scheduling the longer plant shutdowns for maintenance to coincide with the longest neap tides offers the advantages of:

- Performing maintenance when hydrogen production would be intermittent; and
- Taking hydrogen production offline when TEC generation is lowest and so all energy generated can be exported on the 4 MW connection, thus avoiding curtailment caused by the HE not being available.

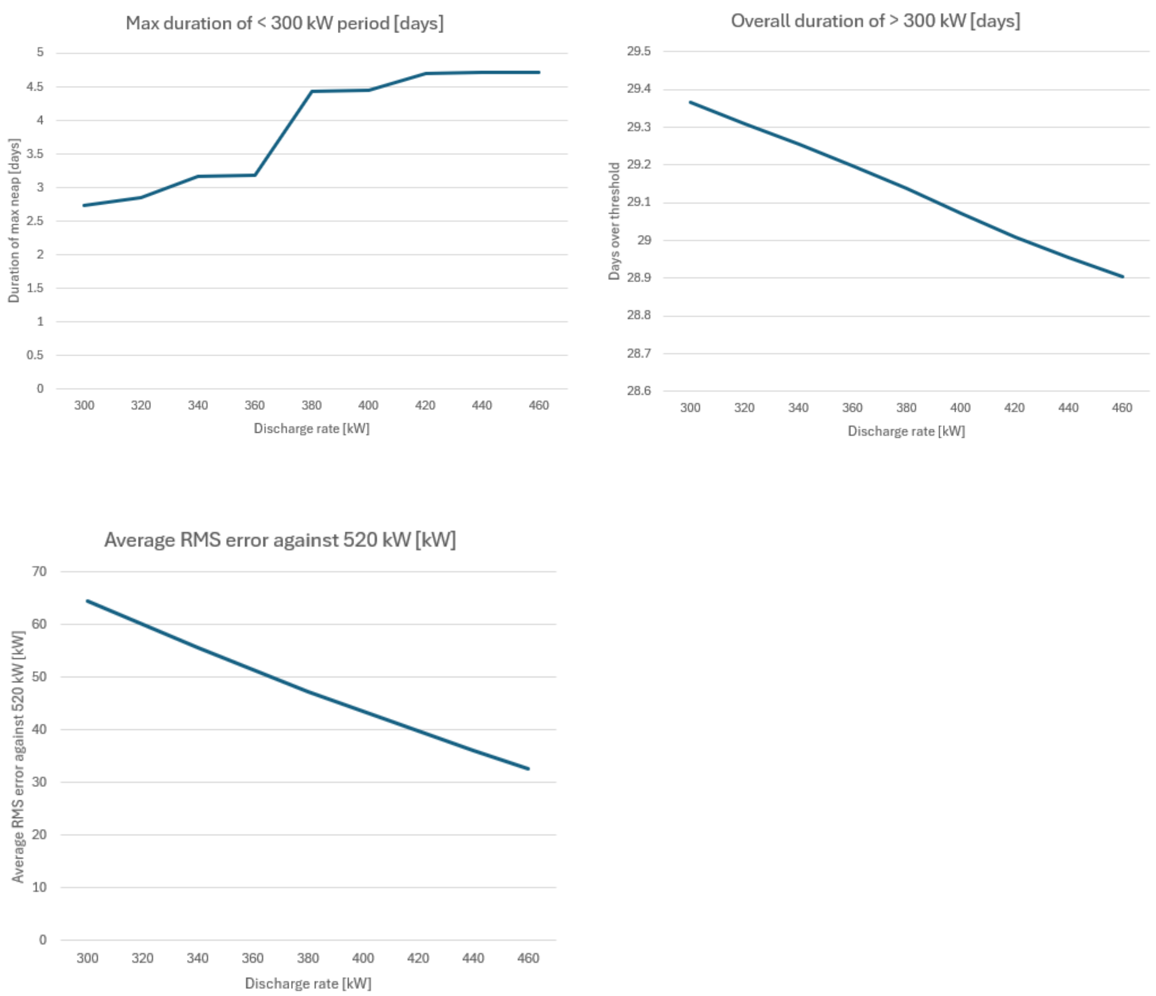

Figure 10 | (i) Max duration of < 300 kW (minimum HE power) period, (ii) overall duration of > 300 kW (minimum HE power) and (iii) average RMS error against 520 kW (optimum HE power) in October 2026.

At the same time, the overall time in the month where minimum power is achieved reduces linearly, as shown in Figure 10 (ii). When minimum power is achieved, it appears to converge on the optimum power for the HE (520 kW). As a result, targeting the discharge rate of 520 kW, which is the optimum HE power, appears to be appropriate.

3.4 Electrolyser operational outage analysis

The work in Section 3.3 shows that there are times when the hydrogen plant would not be operational, but these would be predictable and would occur on an annual cycle, which would fit with maintenance cycles. It was decided to investigate this further to understand how maintenance could be planned around the neap tides and therefore how much time the electrolyser would need to be in stand-by, once maintenance had been planned.

The maintenance for the HE requires production to be stopped for the following durations:

- Weekly: 1 hour
- Monthly: 8 hours
- 6-monthly: 5 days
- Annually: 10 days

For weekly inspections, the short one-hour window allows areas to be entered for visual inspections that cannot be entered when the plant is operational. Monthly checks require more detailed inspection, whereas the 6-monthly and annual inspections require significant work to be conducted. In addition, there may be some follow up work identified, particularly from the longer inspections. It should be recognised that any of these inspections can result in hydrogen production being ceased immediately if a hazard is identified.

The outage analysis began by comparing the electrolyser power for both the 280/300 kW minimum scheme, as shown in Figure 11, and the 280/520 optimum scheme, as shown in Figure 12.

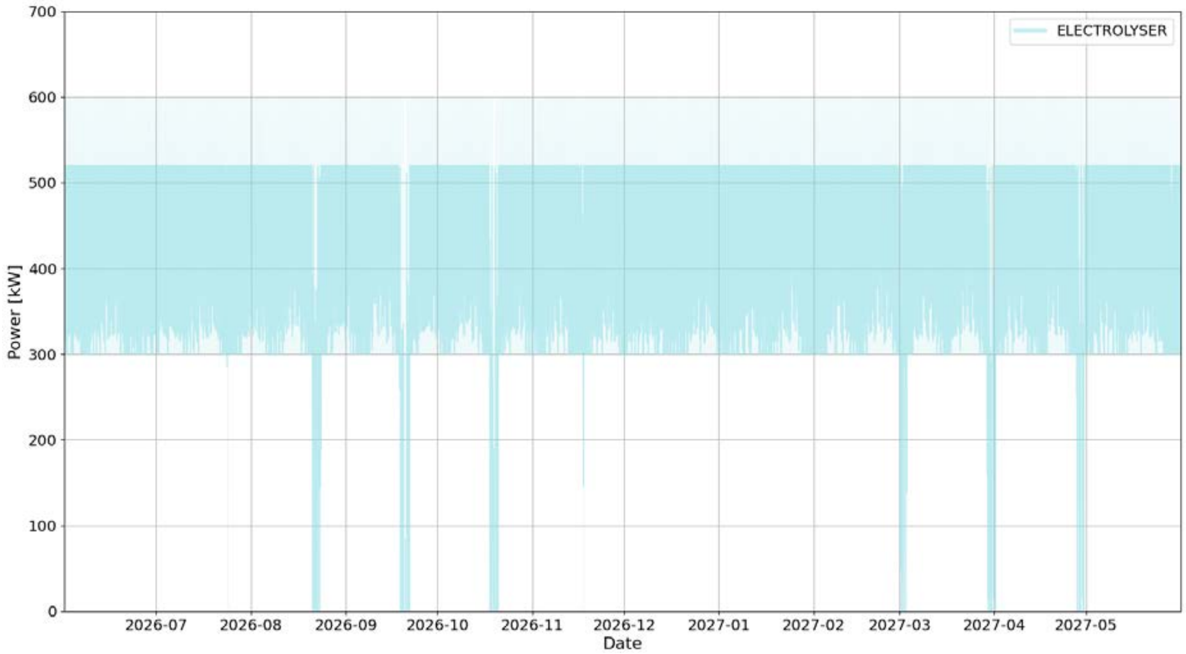

Figure 11 | Electrolyser power June 2026 to May 2027, VFB "minimum" scheme: 280 kW charging 300 kW discharging

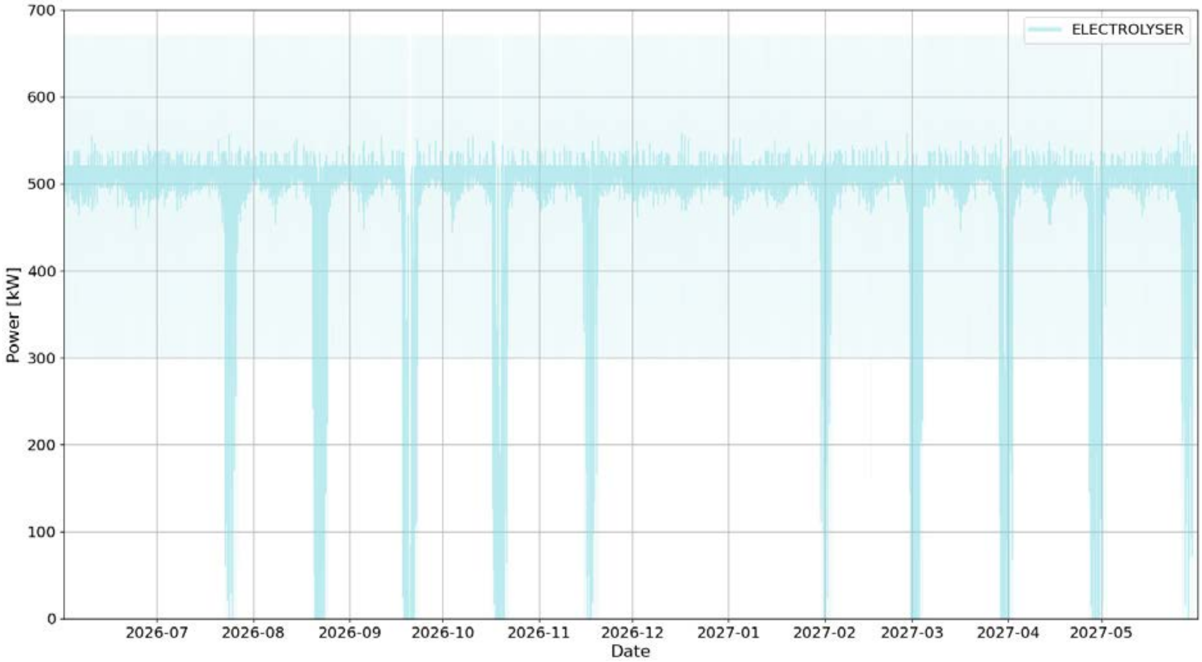

Figure 12 | Electrolyser power June 2026 to May 2027, VFB “optimum” scheme: 280 kW charging 520 kW discharging

Any point where the power to the HE dropped below 300 kW was considered an outage, and the date and duration was recorded in Table 3.

	VFB – 280 kW charge, 300 kW discharge					VFB – 280 kW charge, 520 kW discharge			
Outage type	Start	End	Delta [days]	Delta [h]	<-Difference-> [h]	Start	End	Delta [days]	Delta[h]
Monthly	7/24/2026 7:00	7/24/2026 9:30	0.10	2.5	99.0	7/22/2026 18:30	7/27/2026 0:00	4.23	101.5
Monthly	8/21/2026 0:00	8/24/2026 0:00	3.00	72.0	44.5	8/20/2026 3:00	8/24/2026 23:30	4.85	116.5
Annual	9/18/2026 16:00	9/21/2026 22:00	3.25	78.0	66.5	9/17/2026 22:30	9/23/2026 23:00	6.02	144.5
Monthly	10/18/2026 2:00	10/20/2026 21:00	2.79	67.0	49.0	10/17/2026 2:00	10/21/2026 22:00	4.83	116.0
Monthly	11/17/2026 11:00	11/17/2026 18:30	0.31	7.5	106.0	11/15/2026 3:30	11/19/2026 21:00	4.73	113.5
Monthly					83.5	1/30/2027 11:30	2/2/2027 23:00	3.48	83.5
Weekly					1.0	2/15/2027 18:30	2/15/2027 19:30	0.04	1.0
Monthly	3/1/2027 5:00	3/3/2027 11:00	2.25	54.0	49.0	2/28/2027 4:00	3/4/2027 11:00	4.29	103.0
6-monthly	3/29/2027 16:00	4/1/2027 10:00	2.75	66.0	37.5	3/29/2027 3:00	4/2/2027 10:30	4.31	103.5
Monthly	4/27/2027 22:00	4/30/2027 9:00	2.46	59.0	73.5	4/26/2027 21:30	5/2/2027 10:00	5.52	132.5
Monthly					113.5	5/26/2027 15:30	5/31/2027 9:00	4.73	113.5
Annual total			**16.92**	**406.0**	**723.0**			**47.04**	**1129.0**

Table 3 | Outage calendar comparing “minimum” vs “optimum” VFB schemes

This table shows that periods of outages align with lunar months, thus aligning with the monthly inspection regime. Careful selection of the 6-monthly and annual outages would mean that for the minimum scheme, only four extended monthly outages are required, and these would be extended from 8 hours to 72 hours maximum, making 9.2 days total over the course of a year that the electrolyser would not be able to maintain continuous operation over and above its recommended maintenance windows. In addition, the monthly neap after the 6-monthly and annual inspections provides an ideal window for any follow-up maintenance work identified during the inspections that could not be carried out at the time (but did not require the plant to be shut down).

The optimum scheme causes the number of days that the plant cannot be operated continuously to increase to 34. However, this could be mitigated by using the minimum scheme around these periods to avoid the extended outage and still produce a minimum amount of hydrogen. This would need to happen on nine occasions: five to prevent production stopping and the other four to reduce downtime.

3.5 Detailed electrolyser control behaviour

A close-up view of the optimum strategy during a spring tidal period (Figure 13) suggests that minute-by minute control strategies may be required rather that static set-points.

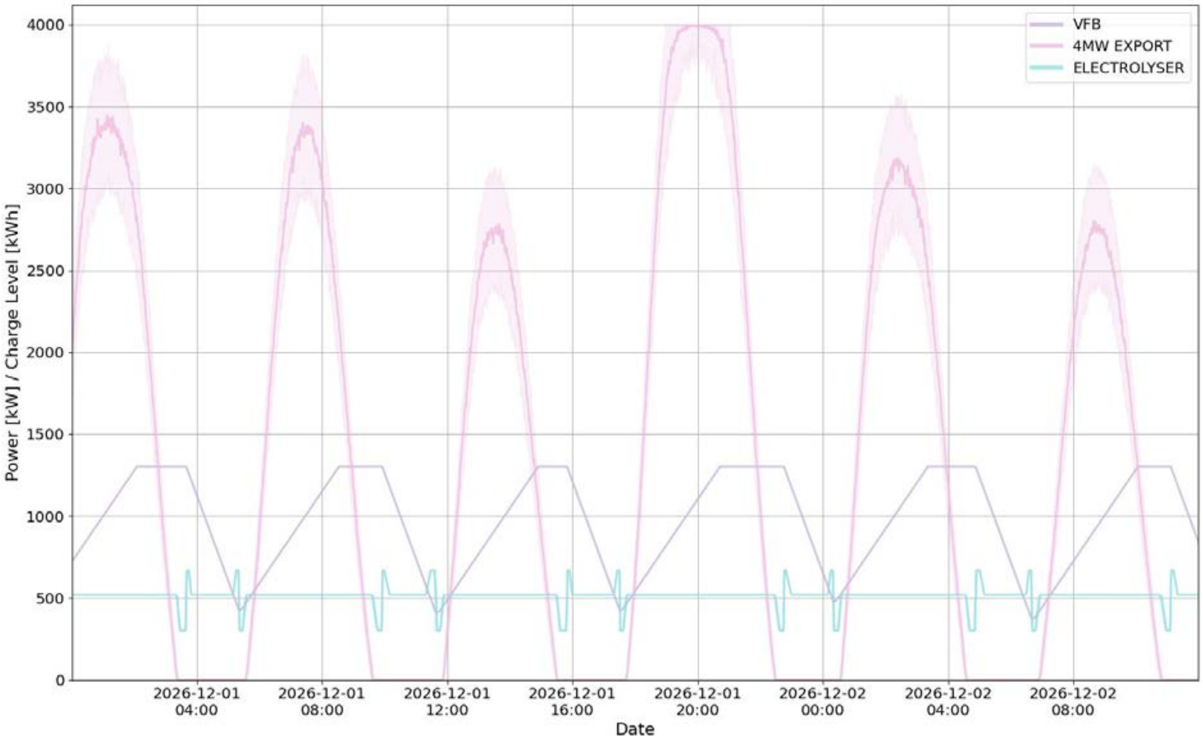

Figure 13 | Close up view of optimum strategy during a spring tidal period

As site power increases:

- 300 kW from TECs goes to HE.
- VFB charges, keeping the HE at 300 kW as no more power can be added.
- Excess power from TECs becomes available. HE reaches optimum power.
- Optimum power is maintained through tidal cycle.
- HE power drops to 300 kW – VFB could probably be discharged earlier as it is typically maintaining/full at this stage.
- VFB discharges, some TEC power is still available, we see a spike in output.
- TEC power drops to zero.
- VFB is discharging, keeping HE at 520 kW.
- TEC power becomes available again. 300 kW is routed to HE, while VFB is still discharging – we see spike in HE power.
- Power becomes available for VFB charge. HE electrolyser power drops to 300 kW.
- Cycle repeats.

The spikes we see between maximum HE power, minimum HE power and optimum HE power by the VFB charge/discharge cycle aligning with the TEC power cycle are caused by the use of static set points in the model. During the periods when the VFB is meant to start or stop discharging, more fine-grained control is required to smooth the output and this is an area that is recommended for further work. This is likely to be a relatively easily solved industrial control problem, since the power budget is more than adequate during these periods.

4 Utilisation of curtailed wind power in the EMEC system

The ERE wind turbine may be selected instead of tidal power in the EMEC system. The previous work has shown that tidal power alone is sufficient to ensure optimum hydrogen electrolyser operations. As the Li-ion battery is on the tidal to grid side only, it has been removed from the system. Also, in order to make the impact that wind may have easier to understand, the VFB has been excluded from the system initially. This results in a revised layout, as shown in Figure 14.

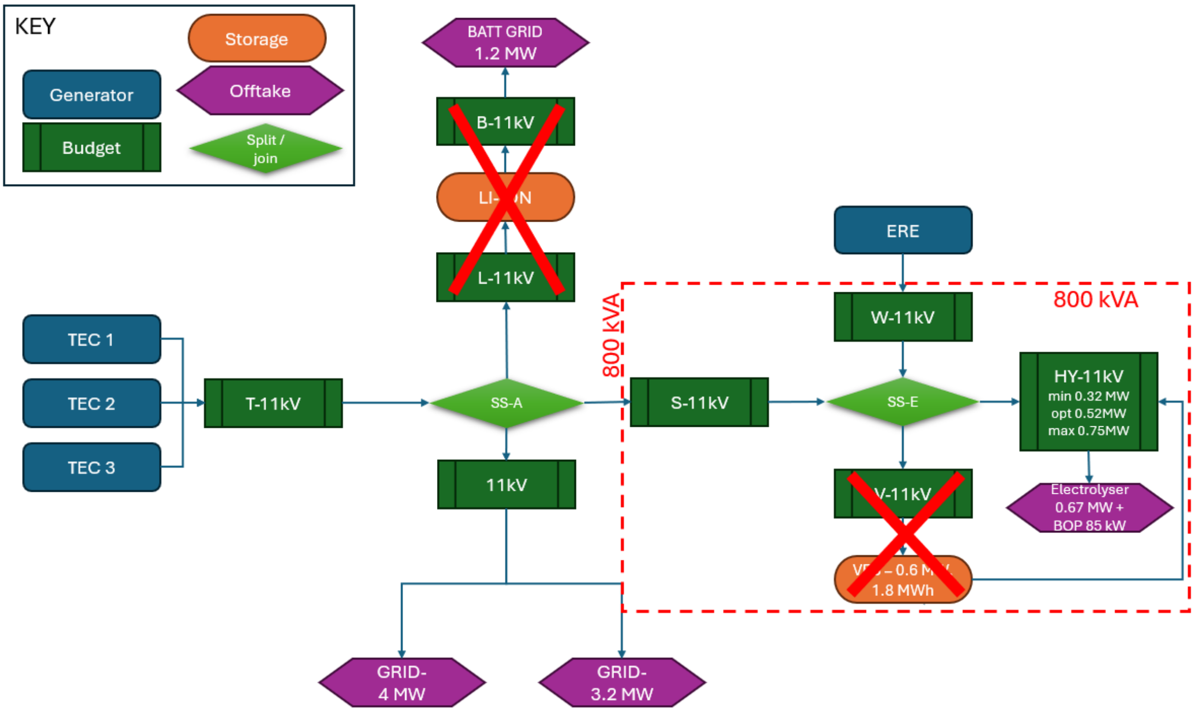

Figure 14 | Revised site layout for wind power integration

The 800 kVA limit still applies. As the electrolyser can only be powered either by tidal or by wind exclusively, two cases were chosen to be modelled:

- Wind is used to power the electrolyser when tidal is 0 MW (i.e. select source on tidal availability).
- Tidal is used to power the electrolyser when wind is 0 MW (i.e. select source on wind availability).

It was assumed that the ERE wind turbine has blade pitch control such that excess power can be trimmed from the system at the wind generator itself to give the desired power level in the EMEC system. This is in line with the specification sheet published for this turbine (Enercon, 2005).

October 2026 appears to be the month for which most curtailment occurs during the modelling period. If the ERE wind turbine is set to power the HE directly as an isolated system, we can see the periods of curtailment, as shown in Figure 15.

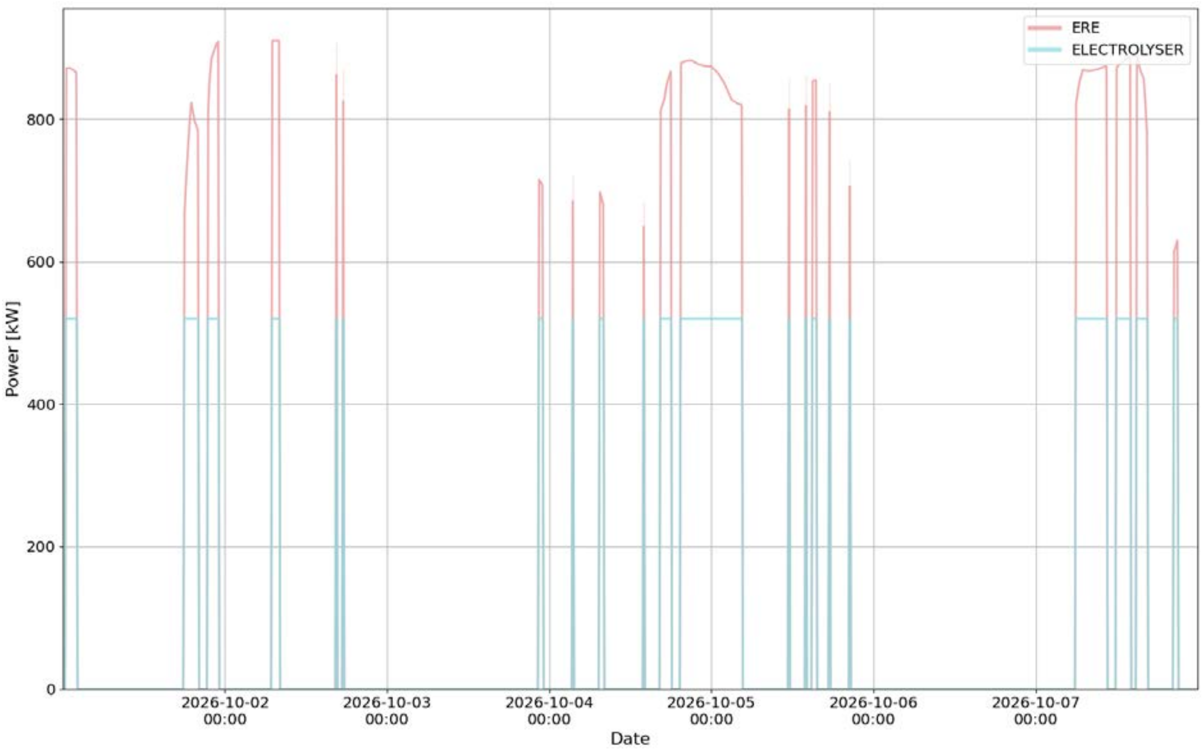

Figure 15 | ERE wind turbine powering HE only (October 2026)

4.1 Switching to wind when tidal power is unavailable (no batteries)

If the system switches between tidal and wind power, thus only using wind power when tidal is unavailable (i.e. 0 MW), then:

- The HE operates during a tidal cycle.
- During slack tide, wind power is used if it is available.
- Switching at 0 MW means that there are temporary drops in the HE power when switchover is attempted.

These assumptions result in a typical daily output as shown in Figure 16.

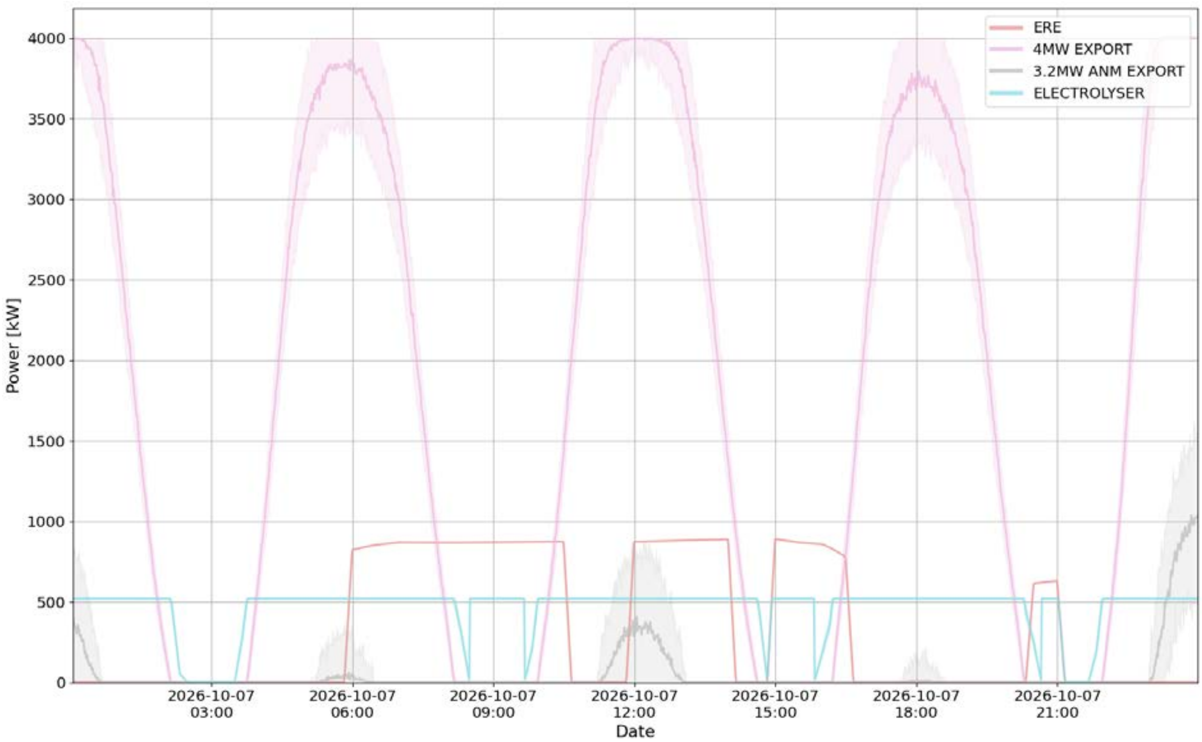

Figure 16 | HE power resulting from tidal and wind, selecting tidal power in preference at a threshold of 0 MW (7 October 2026)

It should be noted that in this modelling the diversion of the ERE power is obtained when there is any curtailment in the system at position 28 in the LIFO stack, which is the position that EMEC has data for. In reality, the ERE turbine is at position 12 in the LIFO stack and hence should be subject to less curtailment. Because the 3.2 MW ANM connection of the EMEC site is only lightly utilised, the site is still exporting a small amount of power (within the curtailment threshold) during this time, whereas it also appears that power is being presented by the ERE wind turbine (i.e. the ERE wind turbine is being curtailed). This is an artifact of modelling on incomplete/inaccurate data and assumptions.

The ERE wind turbine power is therefore an overestimate in this modelling.

It is still worth considering what would happen when curtailment kicks in – assuming both systems were synchronised: one or other of the systems (tidal vs wind) would likely become unavailable before the other – so there remains a need for bridging these interruptions of power.

4.2 Switching to wind when wind power is available (no batteries)

If wind power is selected to power the electrolyser whenever wind power is available (i.e. > 0 MW), then the electrolyser is powered for overall the same periods of time. However, more interruptions to power are seen, as curtailment often starts within a tidal period, and may take effect more frequently than a tidal cycle. This results in more interruptions to electrolyser power, as shown in Figure 17.

Increasing the threshold at which wind power is considered available to the electrolyser to the optimum of 520 kW avoids the appearance of these interruptions, as shown in Figure 18. Instantaneous interruption during switching will still occur and will require some form of uninterruptible power supply to bridge the changeover momentarily.

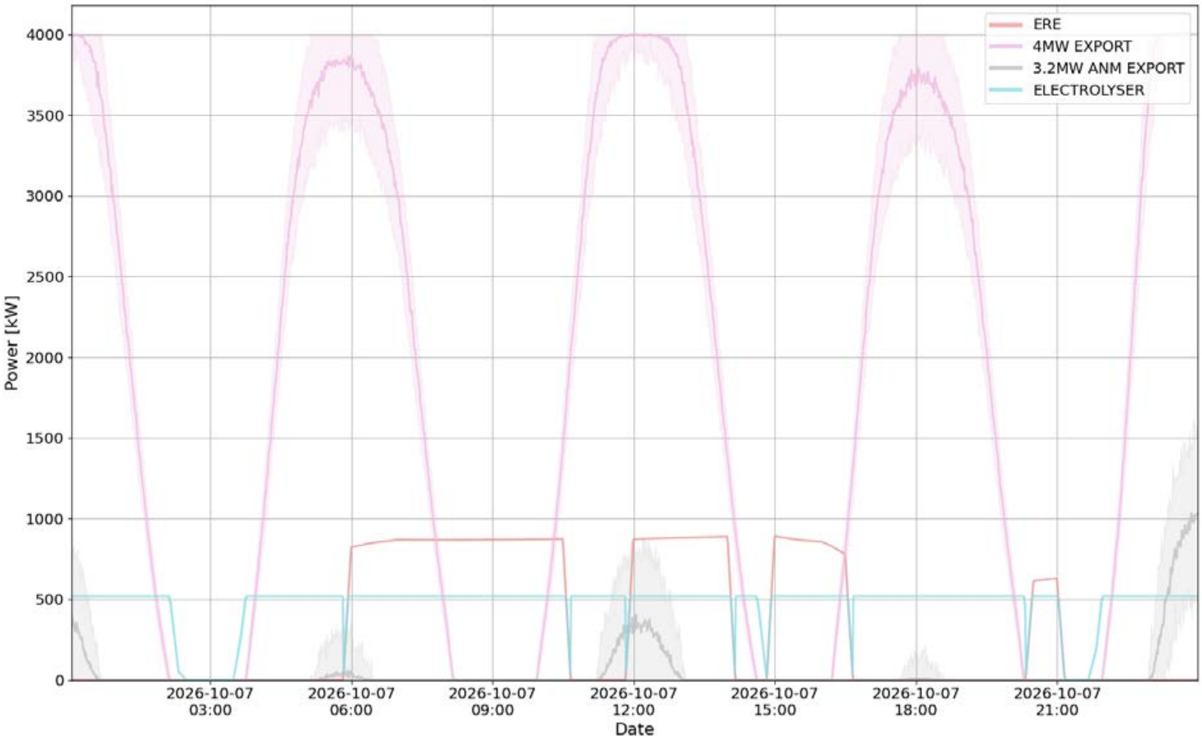

Figure 17 | HE power, selecting wind when > 0 MW of wind power is available (7 October 2026)

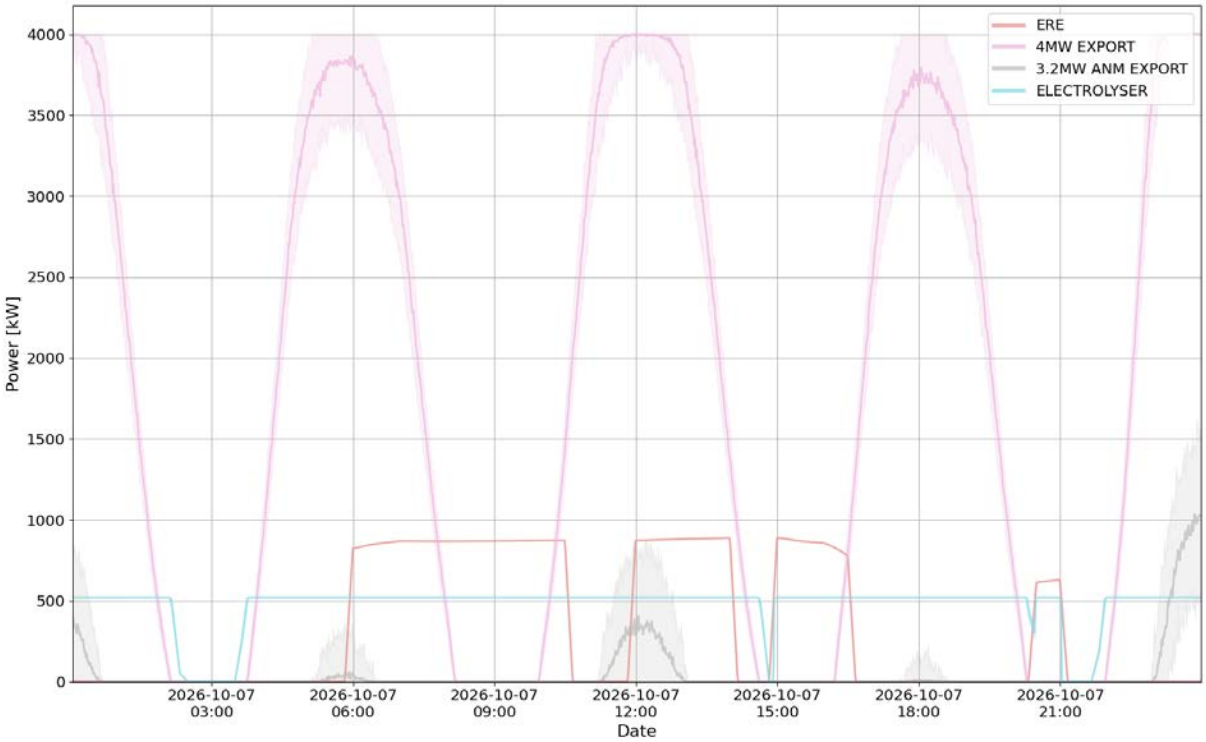

Figure 18 | HE power, selecting wind when > 520 kW of wind power is available (7 October 2026)

The actual behaviour of ANM signalling is likely to cause an asymmetry in switching, but cannot be modelled easily using the data currently available from SSEN. The potential effects of this should be considered when reviewing this modelling and are due to the tidal generation being below the wind generation in the ANM LIFO stack. This means:

- Tidal will be curtailed before wind;
- Tidal power can power the electrolyser irrespective of curtailment, if it is available;
- If curtailment is at a level where tidal is curtailed but not wind, then the electrolyser is still powered, provided tidal has enough power to do so; and
- If both tidal and wind are curtailed, then wind can be used to power the electrolyser without interruption.

These scenarios match the modelling above, so it is considered this modelling remains relevant.

If tidal were above wind in the ANM LIFO stack:

- Wind will be curtailed before tidal;
- Tidal power will therefore typically be available for grid export when wind is curtailed; and
- Wind can therefore be switched to without interruption.

For this scenario, problems will only arise during switching if tidal or wind power are both unavailable, rather than as any consequence of the ANM LIFO positions of either. For the scenario to work, it must be possible for tidal to divert power from grid export to the electrolyser to avoid curtailment ordering effects: having alternative offtake in place helps not only the grid, but also the offtake.

4.3 Sizing of batteries for electrolysis and curtailment reduction

4.3.1 Inclusion of battery and electrolyser in a tidal power system

The required battery size can be obtained by considering the existing VFB, and its minimum power level in both the “minimum” and “optimised” scenarios from Section 3.4 (outside of the nominated outage windows). When considering tidal power only, Figure 19 shows the VFB charge level for the 300 kW discharge scheme i.e. the “minimum” discharge scheme. Figure 20 shows the same for the “optimised” discharge scheme.

Figure 19 | HE power, VFB charge, 300 kW discharge "minimum" scheme, tidal power only.

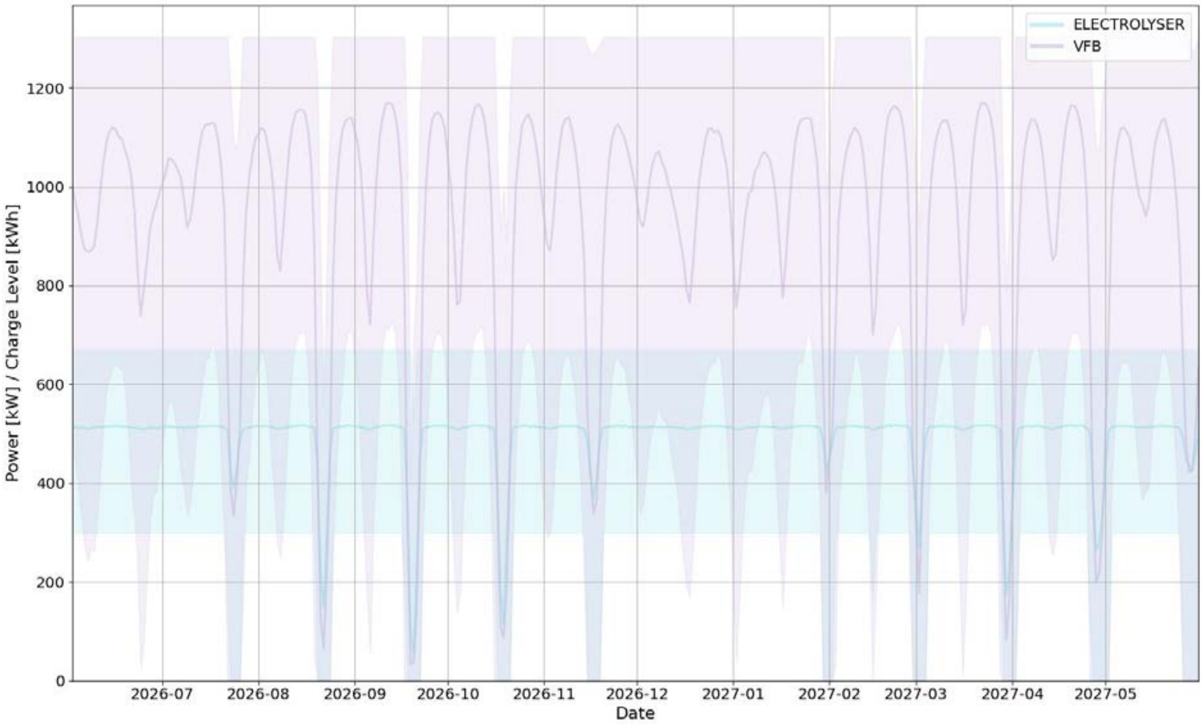

Figure 20 | HE power, VFB charge, 520 kW discharge "optimum" scheme, tidal power only.

The “minimum” scheme produces a VFB minimum charge of 640 kWh over the whole year outside of maintenance windows. This, therefore, (at 75% efficiency rate (Invinity, 2025) on a battery of 1760 kWh) leads to an estimate of ~900 kWh being required. One of the advantages of vanadium flow technology is that it can operate with a high depth of discharge. For this analysis, we have assumed a further 20% headroom – which means for planning purposes, a vanadium flow battery of 900 kWh / 80% = 1.1 MWh is sufficient for the “minimum” scheme. This means that there is an oversizing of the VFB installed at EMEC’s Caldale site.

The “optimum” scheme shows discharges outside of the planned maintenance windows as low as 8 kWh in one case, and 50 kWh in another, although more generally the minimum in any particular month appears to be in the range 150 kWh to 400 kWh. In reality, reduction of the VFB discharge rate is preferable to specifying a much larger battery.

Further work could be done here to provide the economic case for any particular battery size, considering the lifetime operations of the site, and the amount of hydrogen expected to be produced. In addition, the VFB must be discharged below 20% at least once every 7 days in order to maintain optimum operation. This occurs every fortnight as part of this work due to the natural neap cycle, however, this also presents an area for further work as part of the detailed control philosophy. This report begins to demonstrate how both of these areas could be expanded.

4.3.2 Curtailment reduction (tidal only)

The amount of curtailment encountered on the 3.2 MW ANM grid export connection can be summarised by month and compared against the expected generation with no alternate offtake as detailed in Table 4.

Month	Jun 2026	Jul 2026	Aug 2026	Sep 2026	Oct 2026	Nov 2026
Curtailment without offtake **[MWh]**	9.5	20.6	5.3	12.8	17.1	4.2
Curtailment with 300 kW discharge VFB/HE offtake **[MWh]**	1.9	6.9	2.0	3.9	3.6	0.2
Curtailment with 520 kW discharge VFB/HE offtake **[MWh]**	1.9	6.9	2.0	3.9	3.6	0.2
Month	**Dec 2026**	**Jan 2027**	**Feb 2027**	**Mar 2027**	**Apr 2027**	**May 2027**
Curtailment without offtake **[MWh]**	0.0	31.3	43.4	39.2	25.7	20.3
Curtailment with 300 kW discharge VFB/HE offtake **[MWh]**	0.0	7.1	14.9	11.0	5.4	4.7
Curtailment with 520 kW discharge VFB/HE offtake **[MWh]**	0.0	7.1	14.9	10.9	5.4	4.7

Table 4 | Energy expected to be curtailed for the EMEC site June 2026 – May 2027

The act of shifting power to the VFB and HE subsystem avoids significant amounts of curtailment. However, the amount of curtailment avoided does not increase significantly based on electrolyser target power. This is because the charge rate is similar between the two optimum schemes and it is the discharge rate that varies, thus increasing the amount of hydrogen produced. This would have the effect of reducing the levelised cost of the hydrogen for an economic analysis.

The overall amount of curtailment avoidance for the year in the EMEC system is 168.0 MWh in either case, when compared with the generation-only scenario. Diversion of power from export to the VFB / HE subsystem needs to be evaluated against the overall economic case.

4.3.3 Impact of including wind power in addition to battery and electrolyser

A set of comparative plots, when wind is included is given in Figure 21 for the minimum discharge rate of the VFB and Figure 22 for the optimum discharge rate.

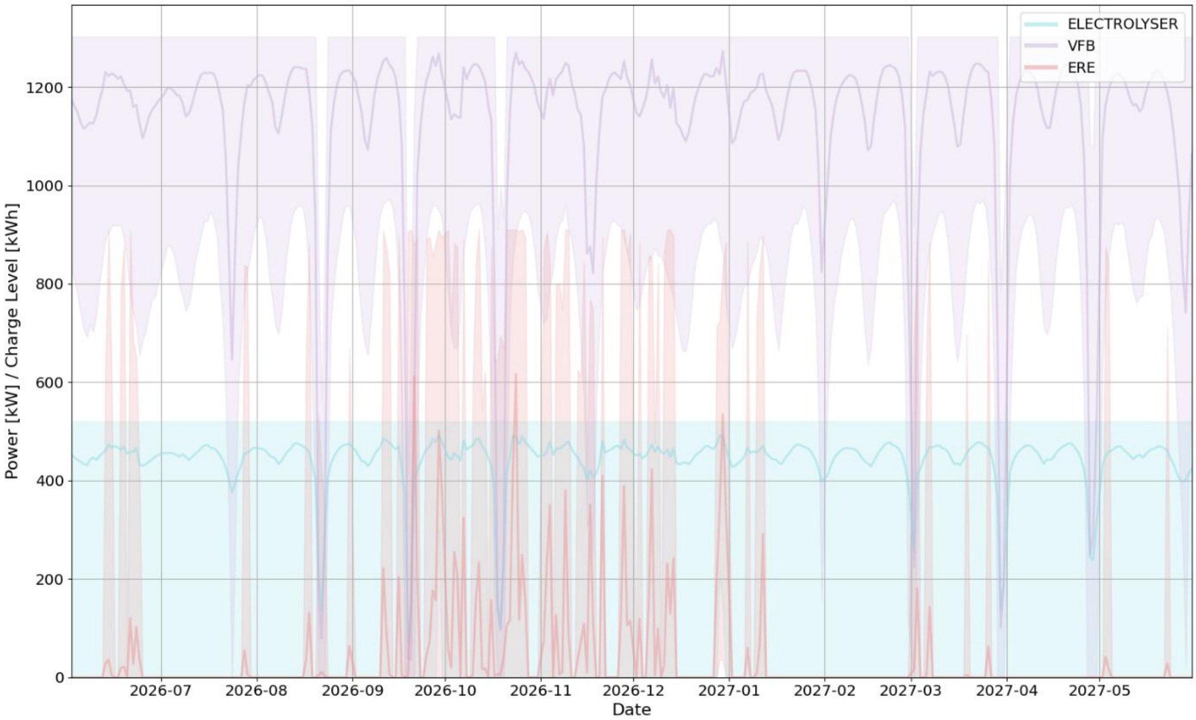

Figure 21 | HE power, VFB charge, 300 kW discharge “minimum” scheme, power supplied by tidal and wind, selecting on tidal > 0 MW

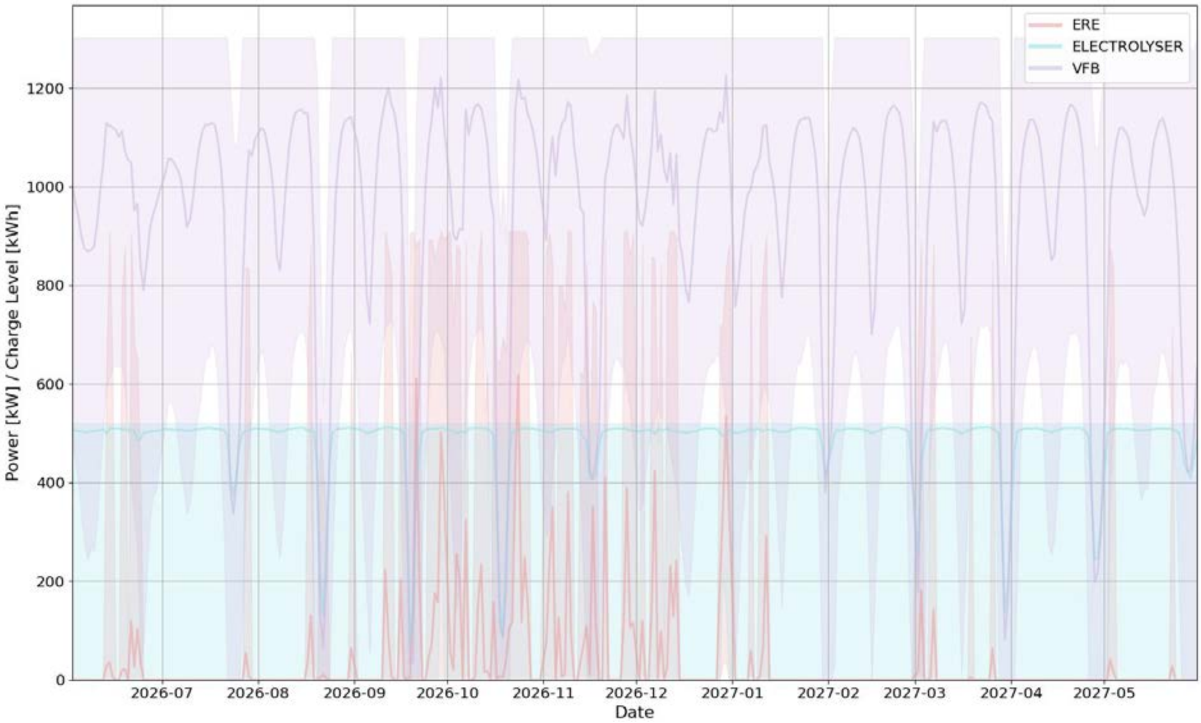

Figure 22 | HE power, VFB charge, 520 kW discharge "optimum" scheme, power supplied by tidal and wind, selecting on tidal > 0 MW

When wind is included, there is no significant difference to the lower VFB charge level (purple lower bound in Figure 19 compared to Figure 21, and again between Figure 20 and Figure 22). As a result, there is no CAPEX benefit from including wind at such a small scale in the EMEC solution.

4.4 Consideration of hydrogen production levels by including wind

Hydrogen yield can be calculated for the tidal-only and tidal-with wind cases of the "minimum" and "optimised" VFB discharge schemes, as shown in Figure 23. The hydrogen production efficiency rate used has been taken from site figures and includes balance of plant. By not operating the electrolyser at its maximum setpoint, the electrolyser has a higher efficiency. For the "minimum" VFB discharge rate, the HE will be operating at its optimum production rate during periods of tidal generation, and so the lower production rate will only occur during slack water, when it is the VFB powering the HE, unless there is curtailed wind available.

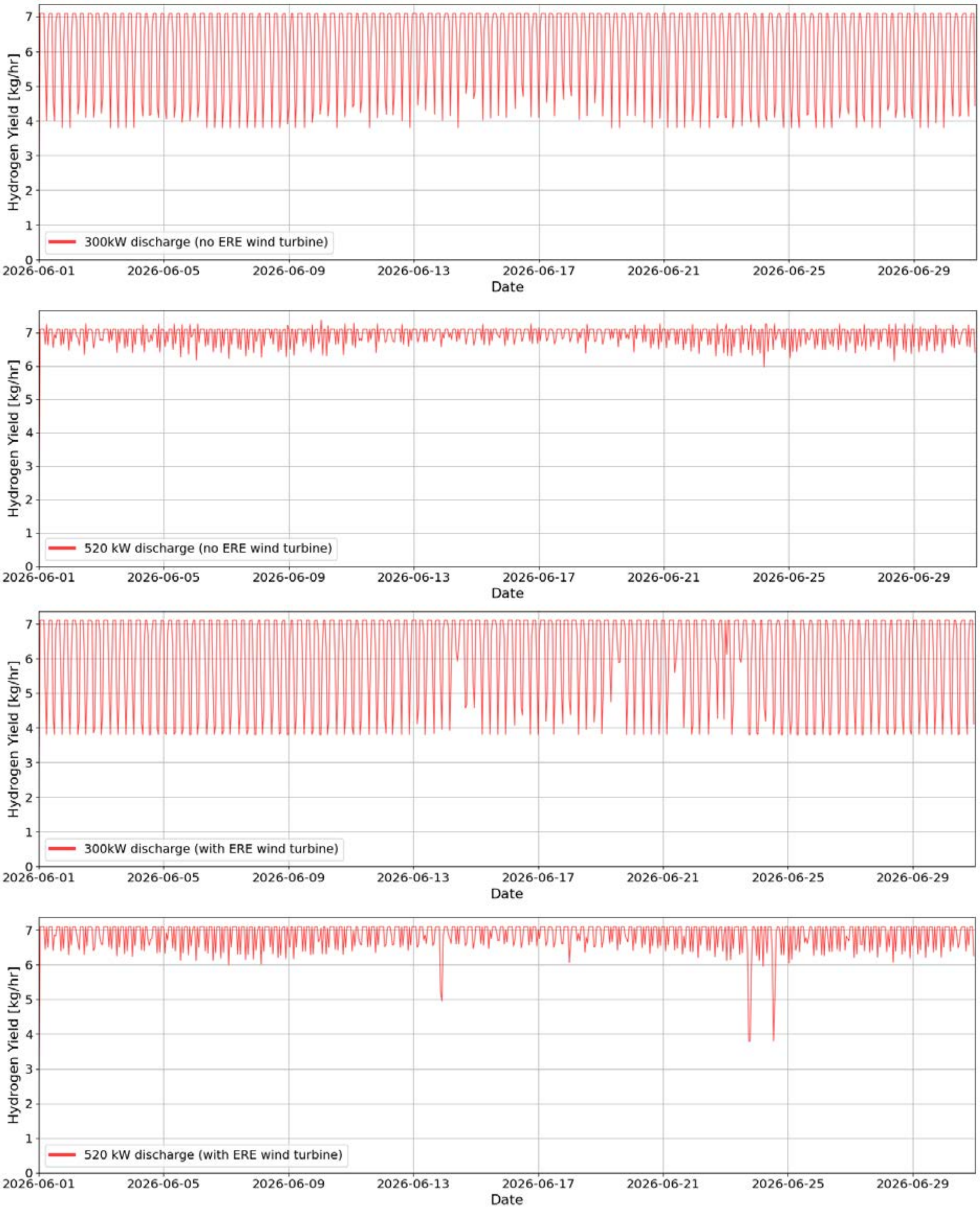

Figure 23 | Hydrogen yield [kg/hr] by hour June 2026 tidal with and without wind, “minimum” and “optimum” VFB schemes

The temporary drop in HE power due to switchover has an effect here and wipes out any gains of adding wind power to the solution, since tidal can power the HE for most of the time, if the VFB is used.

The overall yields for these four scenarios by month can be plotted and is shown in Figure 24. Adding wind has a negligible effect in this situation, due to:

- A poor industrial control strategy;
- The intermittent and short duration of available curtailed wind power, particularly during summer months; and
- The lack of capacity to absorb additional wind power as the system is optimised for tidal, battery and hydrogen.

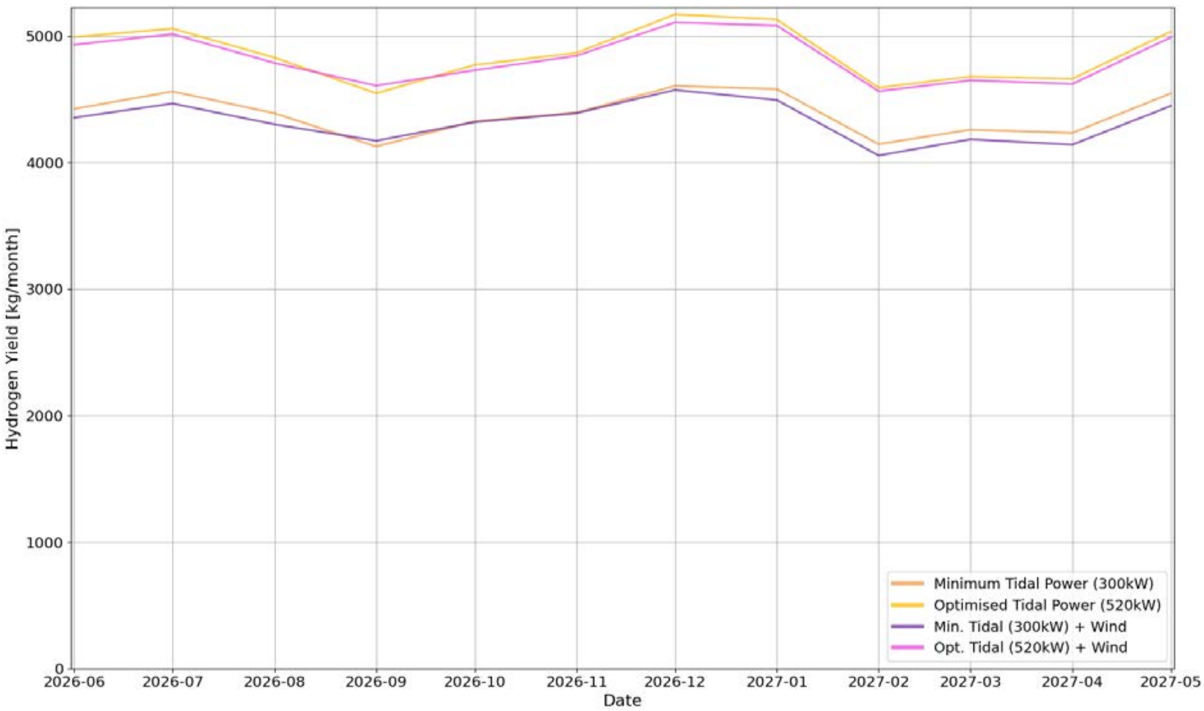

Figure 24 | Hydrogen production in kg by month "minimum" vs "optimised" schemes, tidal vs tidal + wind

Note that for the hydrogen production calculations, "minimum" and "optimised" in this context relates to the VFB discharge rate: "minimum" ensures the minimum power requirements of the HE are met for as long as practically possible. During tidal periods, the HE power will exceed its minimum 300 kW rate, with a target of 520 kW for as much of this as possible. This means that the amount of hydrogen produced is higher than for the HE solely running at 300 kW overall.

4.5 Further Considerations

To achieve a higher capacity factor, the HE at EMEC has been optimised to work with the VFB to operate typically at its most efficient set point, the "optimised" scenario in the modelling, moving to its minimum capacity during neap tides. This enables the electrolyser to:

- Remain responsive and not cause a delay in hydrogen production;
- Avoid frequent venting of hydrogen to the atmosphere during transition from standby to operation: this is particularly important given the increasing recognition, including by environmental agencies, of hydrogen as a potent secondary greenhouse gas;
- Improve the overall lifespan and efficiency of equipment by avoiding frequent cycling between standby and operation; and
- Reduce the levelised cost of the hydrogen.

Wind by its nature is variable, and subject to extended periods of low/zero generation. Curtailment is transient, and may be high frequency, leading to stopping and starting of any load used to soak up curtailed energy: this is a bad fit for the required power profile of hydrogen electrolysers in general, unless some smoothing technologies, such as batteries, are used.

The work done here shows that it cannot be automatically assumed that diverting curtailed energy from a windfarm will automatically vastly improve the economics of a TEC fed HE system, particularly if it has been optimised with a battery system. If the systems are scaled up, then there may be greater consistency of curtailed electricity from the windfarm, but it is important that a detailed economic analysis is conducted. This should include consideration of:

- Layout and expected power output of any wind site or sites in the proposal. Cost of connection, construction and operations and maintenance of said assets;
- Contractual arrangements for power generation and expected payments;
- Expected curtailment, and financial implications of curtailment;
- Whether any hydrogen infrastructure can be powered by alternate means (e.g. grid connection) and the cost of that power provision;
- Inclusion of characteristics of standby mode of HE, together with degradation laws, to allow quantitative assessment of different operational strategies on the efficiency of the system;
- Offsetting cost by connecting directly within curtailment periods according to remaining contractual terms;
- Sale/transport costs for produced hydrogen and route to market, potentially including other applications such as synthetic fuel (and their implications, such as green carbon sources);
- Any smoothing technologies (e.g. batteries of various types and technologies); and
- Any energy market aspects.

It is possible that by considering the full CAPEX/OPEX and total cost of ownership of a hybrid wind, tidal and hydrogen system, that an economic case could be found, resulting in viable hybrid system proposals at scale. Such arrangements need not necessarily be co-located.

5 Potential for grid services and scale up

5.1 Grid services

Commercial services are provided to the National Energy Systems Operator (NESO) under contract. The EMEC site is currently distribution connected and has no relationship with NESO directly. The distribution connection is under ANM control, and this adds a level of conflict when considering commercial services.

Scottish and Southern Electricity Networks (SSEN) are the distribution system operators for the Caldale site and they are investigating how flexibility services can be introduced with a focus on Scotland's Islands. These are currently utilised in the Western Isles[2], but are not currently implemented in Orkney. A recent request for information (SSEN, 2025) to assess the potential for introducing these in other Scottish Islands has identified that for these to be implemented in Orkney, a process needs to be developed for the management of service providers who are connected and controlled by ANM. When this process is developed, it will be possible to understand how and whether the electrolyser can be used to provide these services.

If this service were to be offered, this would be best implemented by moving the set point of the electrolyser from the modelled 65% to within the 35% to 100% operational range when called upon. When operational, the electrolyser is capable of responding within 2 seconds, however, other factors would need to be considered for financial benefits and modelled based on expected frequency and duration of the services, such as any increased rate of degradation to the electrolyser stack. In addition, careful consideration would be needed as to how this would fit with the 800 kVA limit and the ERE wind turbine curtailment switching as these would limit the availability of the service.

5.2 Scale up

The modelling in this report has shown how a TEC and Battery Energy Storage System (BESS) can be combined to deliver an almost continuous power supply to an industrial offtake. The key to this is ensuring that:

- The offtake has a high turndown rate i.e. can stay operational at low power during neap tides;
- The tidal resource is well modelled;
- The battery is sized correctly to the resource and offtake; and
- The predictability of tidal is used to schedule plant downtime and thus maximise capacity factor.

The HE modelling showed that the Caldale example did not provide a lot of opportunity for responding to excess power from the system. However, other industrial opportunities may be able to do this.

One such area is the production of sustainable aviation fuel (SAF). There are various technologies that are being developed to support these and some of these are more able to respond to variable renewables. For example, certain direct air capture systems are passive absorbent for collection of CO_2

[2] Flexibility Services - SSEN

and only require electricity to release the CO_2, which can be performed flexibly in response to available energy surplus.

In addition, the SAF production processes are high temperature. These have large start-up power demands as the plant is bought up to temperature, but the power turndown ratio once the necessary temperatures have been achieved are large. This makes the predictability of tidal suitable for selecting when the various operating models should be implemented to maximise behind the meter electricity.

6 Conclusions and recommendations

It is often discussed how the predictability of TEC generation can be used with energy storage to provide continuous power supply for a behind the meter arrangement. This modelling has shown how this would work in practice. There are large variations in generation across the annual tidal cycle, but the predictability of tides can be taken into account when scheduling activities to meet the needs of the specific offtake industry, such as maintenance operations during neap tides or specific high-energy processes at spring tides.

This work has focussed on the hydrogen production facility at Caldale. It has shown that energy storage can be combined with the hydrogen electrolyser to predominantly negate the need for export on the 3.2 MW connection, thus avoiding curtailment. The ability to still export to the grid on the unconstrained 4 MW connection is fully exploited during spring tides, although less export will take place during neap tides. This analysis has not considered the economic impact of the different offtake mechanisms; however, it has provided a basis from which this could be understood with the correct information.

The extension to the inclusion of the wind showed that careful consideration should be given to the inclusion of intermittent renewable resources, particularly when this is limited to periods of curtailment. For this specific example, the availability of wind generated power only during slack water and the optimisation of the system to maintain the HE setpoint at 65%, means that there is limited capacity to benefit from curtailed power from the ERE wind turbine. Other offtake opportunities may be better able to react to intermittent power, particularly if theses involve multiple high-heat industrial processes that provide opportunities for heat recycling and heat batteries or other applications that can respond to intermittent power availability. This means each system should be carefully modelled at the feasibility stage to understand the optimum configuration.

To ensure the expectations of an offtake contract are met, it is important that modelling exercises include:

- A detailed modelling of the local tidal resource and the TECs. This should be for at least a year and ideally should be for a lunar nodal cycle;
- Consideration of the offtake's turndown rate to understand if it can stay operational at low power during neap tides, or whether it is more economical to close down the plant and not invest in energy storage;
- If required, energy storage, specified and sized to the application, resource and offtake;
- The scheduling and minimising of plant downtime based on the predictability of tidal energy;
- Alignment of plant downtime with TEC maintenance when possible: neap tides are ideal for this;
- Careful consideration of other renewable generation and grid services that could be added to a behind the meter system to understand if and how these ad-hoc supply variations can be best implemented; and
- Incorporation of the modelling into a full economic analysis that includes contractual arrangements for power generation and expected payments.

Consideration should be given to the implication of unplanned stoppages by both the generator and the offtake user and the financial implications of these including whether the grid can compensate. Other aspects of a combined energy system such as control and operational demands (e.g. pre-heating, preservation loads), as well as reactive power grid support (e.g. volt-VAr support) are to be explored in the future.

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