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An assessment of electrolyser portfolio for offshore hydrogen production considering its key properties – efficiency, ramp rate and capacity

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Abstract. Wind-electrolyser systems that produce green hydrogen – including hydrogen-generating offshore energy hubs – have received a lot of attention. The electrolyser capacity in such systems can be arranged in different configurations by varying the location setup of the electrolysers. The setup influences not only the dynamic performance of electrolysers but also the system economics. This paper analyses the differences in the dynamic performance of electrolysers in a centralised and decentralised setup from a technical and economic perspective, when the target is to produce as much renewable hydrogen as possible using today's electrolyser technology. The economic effects of scaling for various wind turbines under different wind conditions are incorporated in the analysis.

Differences in electrolyser efficiency, start-stop, ramping, operation range and scale are modelled, and the models are applied to a case study depicting an offshore energy hub. Using a representative wind profile of fluctuating conditions and considering identical electrolyser ramping and efficiency for the same turbine configuration, the analysis shows that the single electrolyser solution (centralised), where the electrolyser is sited at a substation, gives a better levelized cost of hydrogen than the alternative setup (decentralised) with multiple in-turbine electrolysers.

1. Introduction

With the increasing role of offshore wind and hydrogen in future energy systems, the concept of energy islands is attracting growing interest [1] and has been investigated both in the North Sea [2] and the Baltic Sea [3]. Such islands can function as energy hubs that enable large-scale production of green hydrogen through electrolysis. Electricity currently accounts for much of the production cost of green hydrogen, but with falling renewable power costs, attention is shifting to the second largest cost component – electrolysers and their properties [4].

Different sizes of electrolysers are available [5], and they can be installed in different configurations: offshore centralised and decentralised, and shoreline electrolyser setups. The system setup influences not only the dynamics but also the capital investment and system economics. The purpose of this paper is to illustrate the differences in the operational performance of electrolysers between a centralised and decentralised setup, comparing an analysis where the dynamic properties of electrolysers are considered in the calculation to a typical static analysis - when the target is to produce as much renewable hydrogen as possible using today's electrolyser technology. The system in question is only considering hydrogen as an end product. The economic effects of scaling for various wind turbines under different wind conditions are further combined to the assessment.

An offshore hydrogen energy hub or island is used as a case study to demonstrate the effect of the dynamic properties of electrolysers. The proposed offshore energy islands often involve multiple electrolysers and different system configurations at a large scale [6]. The suggested methodology can be used for onshore wind or other renewable energy setups, including, for example, photovoltaics. Onshore systems are typically smaller in size, but GW-scale projects combining offshore wind and onshore green hydrogen production are under consideration [7].

2. Methodology

Two alternative wind-electrolyser system setups, presented in section 2.1, are compared for an offshore energy island to investigate how hydrogen production differs between the alternative setups. As part of the investigation also different electrolyser capacities, introduced in section 2.2, are tested for the two system systems. How the different properties of electrolysers affect the green hydrogen production is also of interest, as the target is to scale up green hydrogen production to be part of the energy system [8]. The dynamic properties: varying efficiency and ramp rates are discussed in section 2.3.

2.1. Scenarios of system setup

The simulated energy system is an isolated off-grid wind-electrolyser hub. The system consists of wind turbines and electrolysers, and the electrolysers are only powered by offshore wind. In the reference case, the wind farm consists of five turbines. Two system designs are evaluated: a centralised setup that has a single location of green hydrogen production and a decentralised setup with multiple production locations. In the centralised setup, the five wind turbines are collectively connected with cables to one large electrolyser unit, situated separate from the turbines. The hydrogen is then transported via pipelines to the external system. In the decentralised system, a smaller electrolyser unit is sited onto each wind turbine, and hydrogen is transported onward via pipelines.

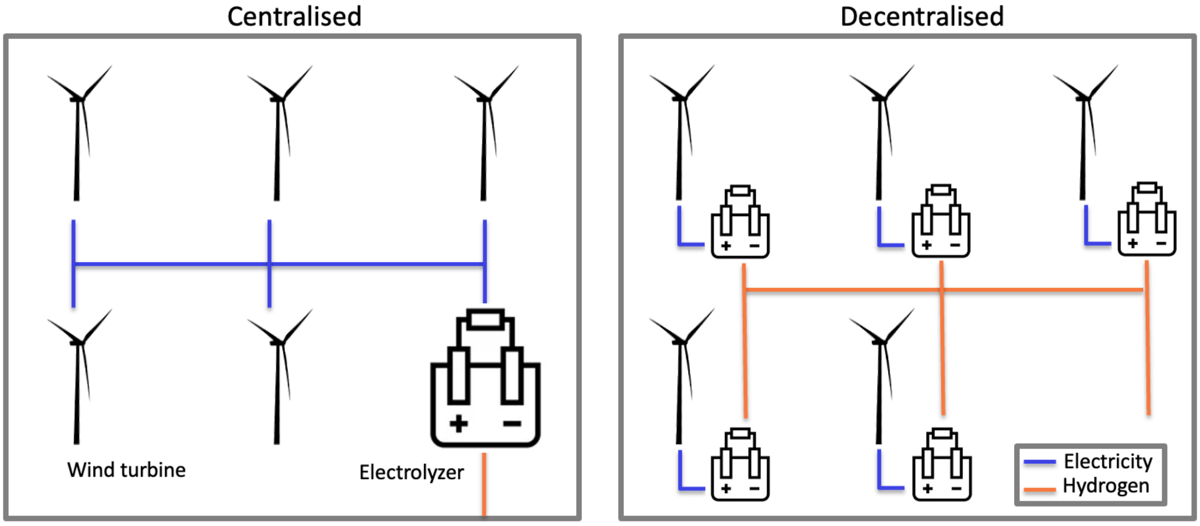

Figure 1. Scenarios of system setup: centralised versus decentralised. Hydrogen is the only product; hence there is only a hydrogen connection to the external system.

2.2. Installed capacity

The installed capacity, i.e. the nominal capacity of an electrolyser determines its potential for producing hydrogen. The capacity is used as a sensitivity parameter, and the aim here is to compare different capacity levels for the centralised and decentralised systems design and how the green hydrogen output differs between the design. The total installed electrolyser capacity is the same for the centralised and decentralised setup. Table 1 shows the different capacities tested.

Table 1. Five different capacity configurations are tested for both a centralised and a decentralised setup.

	Configuration				
Centralised	1 x 2.5 MW	1 x 5 MW	1 x 15 MW	1 x 20 MW	1 x 30 MW
Decentralised	5 x 0.5 MW	5 x 1 MW	5 x 3 MW	5 x 4 MW	5 x 6 MW

2.3. Dynamic properties of electrolyser

Two key dynamic properties of electrolysers are considered in in modelling the isolated offshore wind-electrolyser system. These are efficiency and ramp rate. The following sections describe how these properties are incorporated in the model.

2.3.1. Electrolyser power with ramping. The power consumption of the electrolyser depends on the available wind power. There are some limitations as to how quickly the electrolyser operation can be adjusted. The modelled electrolyser can ramp up and down 20% of nominal capacity per second [9]. To perform a robust analysis, the ramp rate is assumed to be 20% of nominal capacity in ten minutes.

For the first operation time t_1, the electrolyser power P_e is shown in equation 1a. If the wind power $P_{w,t}$ is bigger than the initial electrolyser power P_{e,t_0}, then P_{e,t_1} is the minimum value between:

1. P_{e,t_0} plus the maximum ramp-up power $(R \cdot P_e^{max})$, where R is the ramp rate
2. The wind power
3. The maximum power capacity of the electrolyser, P_e^{max}.

In contrast, if the wind power is lower than P_{e,t_0}, the electrolyser power for t_1 is chosen between the maximum of:

1. P_{e,t_0} minus the maximum ramp-down power
2. The wind power
3. The minimum power capacity of the electrolyser, P_e^{min}.

For all consequent time steps, the electrolyser power is defined similarly as in 1b.

$$P_{e,t_1} = \begin{cases} \min\Big[(P_{e,t_0} + R \cdot P_e^{max}), P_{w,t}, P_e^{max}\Big] & \text{if } P_{w,t} \geq P_{e,t_0} \\ \max\Big[(P_{e,t_0} - R \cdot P_e^{max}), P_{w,t}, P_e^{min}\Big] & \text{if } P_{w,t} \leq P_{e,t_0} \end{cases} \tag{1a}$$

$$P_{e,(t+1)} = \begin{cases} \min\Big[(P_{e,t} + R \cdot P_e^{max}), P_{w,(t+1)}, P_e^{max}\Big] & \text{if } P_{w,t} \geq P_{e,t} \\ \max\Big[(P_{e,t} - R \cdot P_e^{max}), P_{w,(t+1)}, P_e^{min}\Big] & \text{if } P_{w,t} \leq P_{e,t} \end{cases} \tag{1b}$$

When the wind power ramps down between two consequent time steps faster than the electrolyser power can follow, the electrolyser is put into standby state to avoid power deficit. The standby state means the electrolyser is not producing hydrogen but is ready to operate. The stop and restart occur instantly, as no downtime or start and stop times are included. The electrolyser is assumed to be constantly at a hot-start mode, meaning it does not need additional time to heat up before production can begin. Realistically, when the down ramp of wind is too large, the electrolyser would shut down completely because of voltage protection, and it would need more time to start production again, but this is simplified in this investigation.

2.3.2. Varying efficiency. The electrical efficiency of an electrolyser is not constant, which is included as a dynamic effect for the electrolyser. The efficiency peaks at around 30% load and is the lowest at 100% load [10]. As the power consumption varies at different load levels, the hydrogen production rate is calculated with a piecewise function. The hydrogen production curve can be split into sections, where the power consumption per produced kilogram of hydrogen is different. For each section $s \in S$, the A_s (slope between two load points) and B_s (intercept of power at partial load and power consumption) coefficients of the line can be calculated such that the approximated hydrogen production is $A_s P_e + B_s$. The approximation curve is split into sections with partial load steps at 10%, 25% and 50% loads. The electrolyser efficiency is $\eta(j) = \frac{H(j)}{P_e(j)}$, where $H(j)$ is the hydrogen production and $P_e(j)$ is the electrolyser power consumption for different j. The hydrogen production curve is shown in figure 2. The black line shows the non-linear curve and the red line is the linearised approximation curve [9].

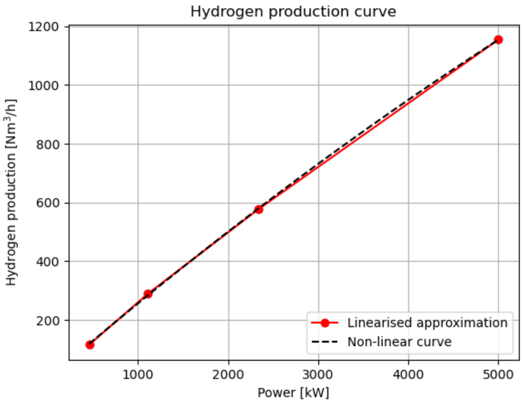

Figure 2. Non-linear and linearised approximation of the hydrogen production as a function of the electrolysers' power consumption.

2.4. Economic evaluation criteria

The performance of the different setups is evaluated by the amount of hydrogen produced. The levelized cost of hydrogen (LCOH) indicates the cost of producing a kilogram of hydrogen. Here, the investment cost, I, and operation and maintenance costs, M, are divided by the total amount of hydrogen produced, H_t. The costs are discounted at the discount rate, r. The LCOH is calculated as in equation 2 [11]. The index t indicates the discounted time frame.

$$LCOH = \frac{\sum_{t=1}^{T} \frac{I_{wt,t}+M_{wt,t}+I_{el,t}+M_{el,t}}{(1+r)^t}}{\sum_{t=1}^{T} \frac{H_t}{(1+r)^t}} \tag{2}$$

The costs used to calculate the LCOH are given in table 2. The isolated system is considered as a whole for the LCOH calculation. The total investment cost of the offshore wind farm excludes the cost of transmission cables. The investment for the electrolyser includes costs for seawater treatment. Often levelized cost calculations include development expenditures (DEVEX) and abandonment expenditures (ABEX), but these are not included in the assessment as these are costs related outside the wind farm lifetime. As the system is assumed to be off-grid, market costs, such as trading and imbalance costs, corporate tax, etc., are not included in the calculation. The cost of electrical array cables and hydrogen pipelines within the farm are also overlooked. The LCOH results can be viewed in table 4.

Table 2. Input parameters for the LCOH calculations for hydrogen production as in Wei He et al. [11].

Input parameter	Description	Wind farm	Electrolyser
Unit Capex €/kW	I	3500	800
Annual O&M share of Capex %	M	3	3
Discount rate %	r	5	5

2.5. Wind power data

The wind power data used for the simulations represent a 30 MW wind farm consisting of five 6 MW turbines. The active wind power time series used is given in 10-minute average values, meaning a large fraction of the fluctuations has already been removed. The farm has an annual power capacity factor of 0.56, and the mean active power for the year is 3.3 MW per turbine (this equals 29 GWh per year). Table 3 shows an overview of the reference scenarios used.

Table 3. Overview of the reference scenario.

Park size	30 MW
Mean wind speed	9.98 m/s
Wind time series	10 minute intervals
Turbine	5 x 6 MW turbines
Annual energy production	5 x 3.3 MW = 144 GWh
Different size of electrolysers	2.5 MW, 5 MW, 15 MW, 20 MW, 30 MW

Figure 3 shows the load duration curve of the different wind turbines. The exceedence is equal to the capacity utilisation rate. Turbine 5 (WT5) has the highest load utilisation and turbines WT1 and WT4 have the lowest. All turbines operate at full load for around 35% of the time. Figure 4 show an example of the active power for one day. Both figures show that the power for the different turbines varies, with some of the turbines having more fluctuations than others. The average in figure 4 shows that when the power from different turbines are combined and considered as one source, the power fluctuations are smoothed. The standard deviation of the active power, meaning how much the measured values differ from the mean value, of the active power is approximately 2.5 MW for each turbine. The turbine power outputs are highly correlated. The most correlated turbines are WT3 and WT5, with a correlation coefficient of 0.93. The least correlated are WT1 and WT4, having a correlation coefficient of 0.82.

The capacity factor is calculated by dividing the active power by the nominal power capacity. Figure 5 shows the capacity factors per turbine for the active wind power for each month of the measurement year. The capacity factors vary slightly between the different turbines. The mean value, i.e. the monthly average, is shown with a black horizontal line in the bars. In January, the mean value is around 0.9, whereas in July, it is around 0.2. This means that in January the average capacity factor is higher, indicating that the month has higher wind speeds for the measured site. The coloured bars show how 50% of the capacity factors are distributed. The other 50% are indicated with the vertical black lines.

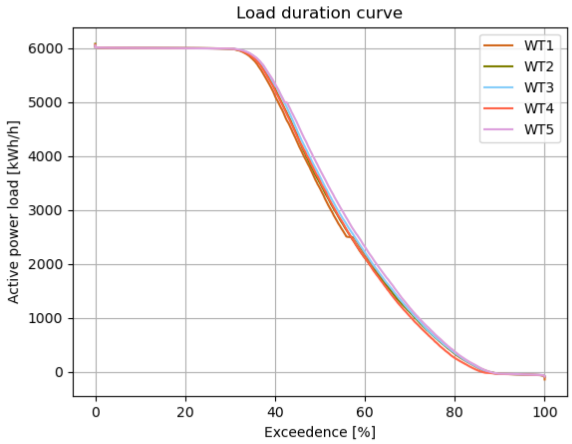

Figure 3. Load duration curve of active wind power per turbine.

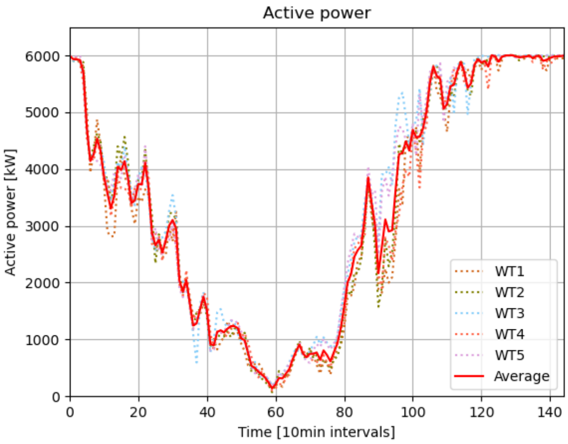

Figure 4. Active wind power for 1.1.2018 for all turbines and showing the average.

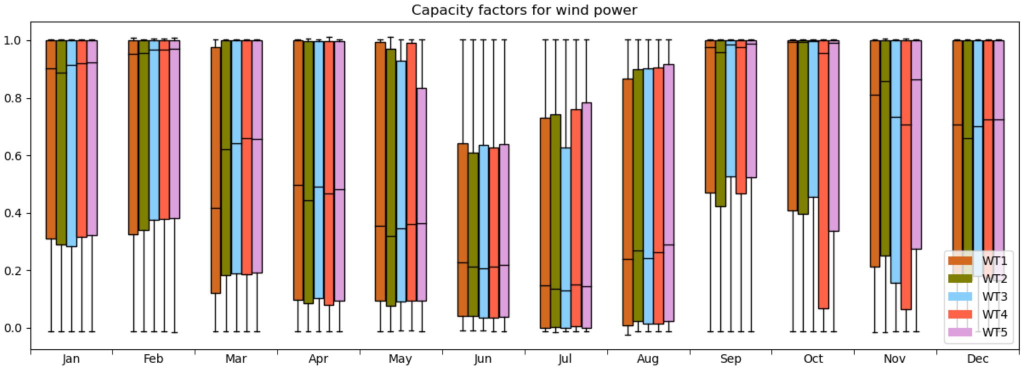

Figure 5. Wind power capacity factors for the five wind turbines in the reference case are shown as monthly distribution of the mean values.

3. Results of dynamic effects

The different dynamic properties of the electrolysers discussed in the previous section are shortly summarised with a short description of the effects they have on the operational performance.

1. *Ramping:* Inclusion of ramp rates decreases the hydrogen production, due to standby of production when ramp down limits are violated.
2. *Efficiency:* Varying efficiency ensures a better utilisation of available power; hence hydrogen production increases.
3. *Selection of size:* With a larger electrolyser, volume of hydrogen production increases proportionally less than cost of production.

The effects are analysed in more detail in this section.

To illustrate how the inclusion of dynamic effects influence the calculations, the system is first modelled excluding the dynamics. A single wind turbine and a representative electrolyser are shown, where the nominal capacity of the electrolyser is set to 1 MW, and the wind turbine has a capacity of 6 MW. Disregarding the ramping limits and assuming constant efficiency, the electrolyser power level will follow the wind power.

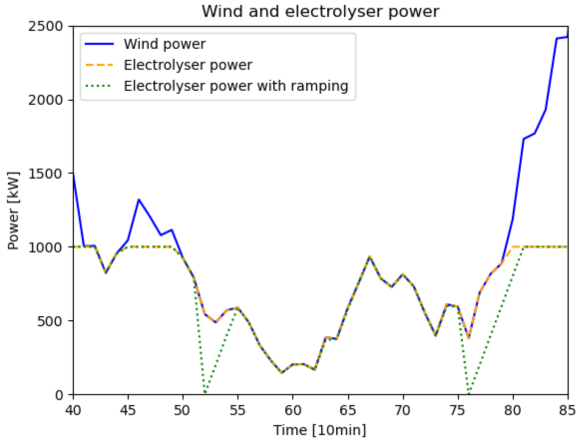

Figure 6. Aggregated wind and electrolyser power with and without ramping.

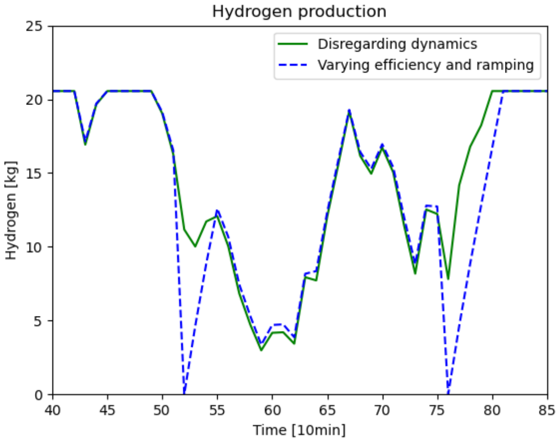

Figure 7. Hydrogen production disregarding versus including electrolyser dynamics.

Figure 6 shows the available wind power as a blue line and the electrolyser power without ramp rates as a yellow dashed line. The green dotted line shows the electrolyser power when ramp rates are included. As mentioned in section 2.3.1, the electrolyser will go into standby state when the wind down-ramp is larger than the electrolyser ramp rate. It is assumed that the electrolyser is able to instantly transition from standby to production mode.

Figure 7 shows the dynamic effects of including both ramp rates and varying efficiency on the hydrogen production. The green line indicates the number of kilograms of hydrogen that can be produced within each time interval, without ramping and assuming constant efficiency. The blue dashed line illustrates the combined effect of ramping and varying efficiency. The ramp rates reduce the hydrogen production because of the power limitations (as seen in figure 6), whereas using varying efficiency gives a slight increase in production in some time steps. Using varying efficiency makes it possible to better utilise the available power, as the electrolyser consumes less power to produce a kilogram of hydrogen at lower load levels.

3.1. Centralised versus decentralised bundling of electrolyser capacity

To determine the dynamic effects of electrolyser capacity location, the operational performance is calculated for a centralised and a decentralised electrolyser setup. Five different total electrolyser capacities for the wind farm are tested. The cases analysed are summarised in table 1.

Figure 8 shows the annual green hydrogen production for a total electrolyser capacity of 5 MW, comparing both the effect of dynamics and the system setup. Disregarding dynamics, the annual hydrogen production is approximately 1.2% higher for the centralised solution than for the decentralised configuration. With dynamics, the difference is 1.9%. The highest hydrogen production is calculated for the centralised setup disregarding dynamics, whereas the decentralised setup with dynamics leads to the lowest production. This is due to the decentralised setup being more exposed to fluctuating wind power and the dynamics (mainly the ramp rates) decreasing the production. The total annual amount of hydrogen produced with dynamics in each setup can be seen in table 4. The smaller the system, the bigger the difference in production between centralised and decentralised setups. The larger capacities produce a smaller difference, as can be seen in table 4. The difference is calculated in comparison to the centralised system.

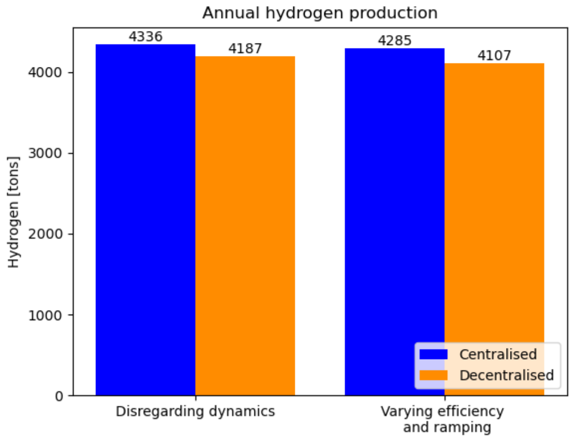

Figure 8. Hydrogen production for 5 MW electrolyser capacity, comparing 5 x 1 MW and 1 x 5 MW setups.

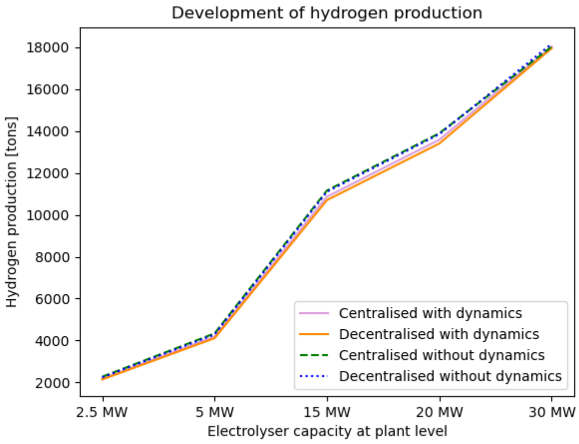

Figure 9. Increase in hydrogen production for different total electrolyser capacities, calculated with and without dynamics.

As realistic calculations would always include the dynamic properties, results are only shown with the dynamics.

3.1.1. Annual hydrogen production. Figure 9 shows the hydrogen production when the nominal capacity is changed. The results are calculated from the electrolyser perspective only. The reason for the differences in hydrogen production between the centralised and decentralised setups is that the smoothing of wind power is not considered in the calculations. For the centralised setup, the wind power from all five turbines is fed into one electrolyser, and the aggregation of power smooths out the individual fluctuations that occur in the turbines. In the decentralised setup with in-turbine electrolysers, there is no smoothing effect. For the turbine-specific fluctuations, the electrolyser ramp-down ability is often lower than the wind ramp-down, meaning the electrolyser will stop production more frequently. A more frequent standby rate entails less hydrogen being produced. The wind power fluctuations are discussed earlier in section 2.5.

Table 4 also shows the annual excess wind power, meaning the electricity not used for hydrogen production out of the annual total 144 GWh produced. The wind utilisation rate shows the share of power used for hydrogen production. As the modelled system is assumed to be an isolated off-grid system with hydrogen as the only energy product, the excess wind power would be curtailed, entailing a lot of energy losses.

3.1.2. Levelized cost of hydrogen. The aim of this investigation is not to give accurate estimations of LCOH, but rather illustrate the effects of the electrolyser dynamics and the system setup. All cost inputs are rough estimations. The investment costs for both the electrolyser and wind system are included. Table 4 shows that for the small electrolyser capacities, the LCOH is very high and decreases when capacity is increased. The investment costs for both the electrolyser and wind system are included. Furthermore, the hydrogen production is relatively small and capital investment weighs heavily on the overall system cost. The hydrogen production increases with increase in electrolyser capacity, with capital investment in the electrolysers also increasing. However, the wind investment stays the same, allowing the LCOH to decrease.

The electrolyser dynamics only influence the Opex, which is a very small part of the total costs. Increasing capacity increases the electrolyser Capex linearly. To be able to justify which setup is economically the most feasible, a full economic analysis should be made, calculating the net present value (NPV) and internal rate of return (IRR) for the whole project.

Table 4. LCOH (€/kg) and the total amount of hydrogen produced (tonnes of H_2) for different farm setups and accounting for the electrolyser dynamics. The bottom two rows show the difference in annual hydrogen production between the centralised and decentralised case, disregarding dynamics.

		Centralised			
Configuration	1 x 2.5 MW	1 x 5 MW	1 x 15 MW	1 x 20 MW	1 x 30 MW
Total H_2 (ton)	2181	4187	10865	13587	18032
Excess wind GWh/year	128	112	57	35	2
Wind utilisation rate %	12.4	23.7	61.0	75.9	98.8
LCOH (€/kg)	49.26	26.20	10.85	9.00	7.31
		Decentralised			
Configuration	5 x 0.5 MW	5 x 1 MW	5 x 3 MW	5 x 4 MW	5 x 6 MW
Total H_2 (ton)	2137	4107	10705	13406	17959
Excess wind GWh/year	129	113	60	39	3
Wind utilisation rate %	11.8	22.7	58.8	73.5	97.9
LCOH (€/kg)	51.58	27.34	11.26	9.30	7.40
Difference in H_2 production	2.1%	1.9%	1.5%	1.4%	0.4%

4. Discussion and conclusions

This work investigates the effect of hydrogen-producing electrolysers' dynamic properties on the operational performance of a wind-electrolyser system and how the performance is affected by the electrolyser capacity configuration. Applying the proposed modelling approach, the centralised setup, where a single electrolyser is sited at a substation, gives a better levelized cost of hydrogen than the decentralised setup with multiple in-turbine electrolysers.

The model is simplified to only consider selected dynamic properties of the electrolysers. It also neglects the effects of the surrounding system on the electrolyser operation. The following are suggestions on how the analysis could be extended in future work.

Electrolyser start and stop times could be included in the model to determine if start-stop rates affect the optimal operation of an electrolyser. Currently, when the ramp-down limit is violated, the electrolyser is put into standby state and assumed to be able to restart instantly in the consequent time step. Realistically, the electrolyser has multiple states: operation, standby and off [12]. A cold start from an off state requires more time for the electrolyser to heat up and start production than a hot start from a standby state. Tracking the electrolyser states, and activating production when electricity prices are low, can help optimise the cost of the system. Using forecasting, it could be determined if the electrolyser should be set into a standby mode or turned off, depending on how long the prices are expected to remain high.

Other possible future investigations could include the electrolyser degradation, which will lower the operation capacity over time. Different loss factors and their impact on both centralised and decentralised systems are relevant to study - including loss estimations at a system level, which could potentially impact the energy efficiency and system economics between a centralised and a decentralised setup. Also, analysing larger gigawatt-scale green hydrogen plants and comparing the results to assessments already made, e.g., [13].

To conclude, there are many possible wind-electrolyser system setups that impact system performance and economics in different ways. Consideration of electrolysers' dynamics properties is essential for making valid estimations of green hydrogen production. Optimal sizing and capacity configuration of electrolysers, within a system perspective, are necessary to maximize the utilisation of available green energy for hydrogen production.

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