A COMPARISON OF ECONOMIC BENEFITS OF HYDROGEN PRODUCTION IN DC BASED WIND FARMS

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Abstract: This paper presents the economic evaluation of offshore hydrogen production from a DC wind farm. Depending on local regulations, wind farm operators sell electricity on the EPEX Spot market or receive fixed feed-in payments. The introduction of an electrolyzer provides the ability to produce hydrogen. Using real-world wind data, an optimal strategy to improve the economic viability of adding an electrolyzer to a DC wind farm is developed. The performance of this strategy is examined under different scenarios of electricity and hydrogen market prices.

Keywords: offshore, wind farm, hydrogen, profitability

1 Introduction

The urgent transition from fossil fuels to renewables and the decarbonization of the electricity, gas, heat, and transport sectors is a challenge that requires innovative solutions [1]. Although wind and solar energy through wind farms and photovoltaic farms offer a viable path for the electricity sector, a long-term strategy must include all of the aforementioned sectors. The complete electrification poses significant challenges and highlights the importance of hydrogen as an alternative energy carrier. Hydrogen's versatility makes it a promising solution, especially in areas where electrification is impractical [2]. It can replace conventional fuels in energy-intensive applications, enabling zero-emission use cases. In [3, 4], a hydrogen roadmap for the USA is presented, which slowly scales up from trucks and transport vehicles before 2030 to large-scale hydrogen applications in the heating and steel industries. This will empower energy-intensive sectors to achieve zero emissions by facilitating large-scale production of green hydrogen. Commercial hydrogen production relies on two main requirements: DC voltage, necessitating the use of rectifiers to connect it to the AC grid [5], and a substantial supply of renewable energy, which can be provided by wind farms.

The offshore wind sector has attracted much attention due to sufficient wind energy, low wind shear, high power output, and low land occupancy [6]. As of 2021, China leads in installed offshore wind capacity with a total of 26.3 GW [7]. This is followed by the United Kingdom with 12.3 GW and Germany with 7.8 GW of total installed capacity [7]. Similar to the AC power grid, the state-of-the-art design of collector grids for wind farms is based on alternating current. However, in recent years, the amount of onshore high-voltage direct current (HVDC) transmission has increased, with a break-even distance of 50 km for cables and 600 km for overhead lines [8]. For offshore transmission, the break-even distance is 150-200 km. Since transmission capacity decreases with distance, wind farms more than 100 km from shore are typically equipped with DC connections [9]. To date, no projects have been reported using a DC collector grid to connect the wind turbines to the shore connection platform. However, studies of similar medium voltage grids show an increase in grid efficiency when a DC grid is used to supply only DC loads [10], which will be discussed further in this paper.

This paper contributes to the field of renewable energy systems by performing an economic analysis of the operation of offshore wind farms under different electricity and hydrogen price scenarios. Our approach is characterized by using real-world data, including market data over several years, to provide a solid foundation. In addition, the initial cost of the electrolyzer is considered. Most recent studies in this area are mainly based on the daily resolution of wind data or focus on conceptual optimizations, mainly due to the limited availability of high-resolution operating data [11]. Similarly, purely economic considerations are often made without taking into account actual operating conditions [2, 12]. Moreover, the advantages of DC grids are often briefly mentioned in the literature [13, 14]. This study attempts to fill these gaps by considering detailed market conditions and operational data, thereby contributing to a clear understanding of hydrogen integration challenges and potential in renewable energy systems.

The paper is organized as follows: Section 2 presents the methodology used in the study, detailing the Alpha Ventus wind farm, the data records used for the analysis, and the electrolyzer layout. Section 3 discusses the regulatory framework for wind parks and the EPEX market. Next, section 4 presents the economic benefits of embedding an electrolyzer in the wind farm, considering several years of energy market data and different hydrogen prices. Also, recommendations for regulatory adjustments are given. Section 5 examines the operational advantages of the DC wind farm. Finally, section 6 concludes the paper by summarizing the key findings and their implications for the renewable wind energy sector. It also suggests areas for future research.

2 Modelling of the wind farm

This study uses the Alpha Ventus research wind farm as a reference model. Operational since 2010, it is Germany’s first offshore wind farm, located 45 km north of the island of Borkum (see fig. 1). It consists of 12 turbines from two manufacturers positioned in 30 meters of North Sea water.

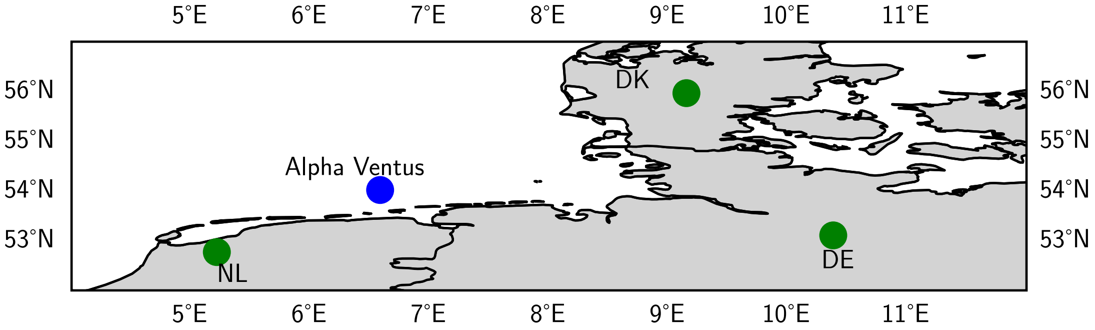

Figure 1: Geographic location of the research wind farm Alpha Ventus.

The turbines involved are six REpower 5M126 5MW turbines (AV01-AV06) and six Areva Wind GmbH Multibird M5000 turbines (AV07-AV012), see fig. 2, with the shore connection located near the AV012 turbine [15]. The operation data for the wind farm, essential for this research, were provided by the RAVE (Research at Alpha Ventus) initiative, which was funded by the German Federal Ministry of Economic Affairs and Energy based on a decision by the German Bundestag and coordinated by Fraunhofer IWES. Additionally, the nearby FINO1 offshore research platform, located close to the wind farm (see fig. 2), contributes wind data measurements at various heights.

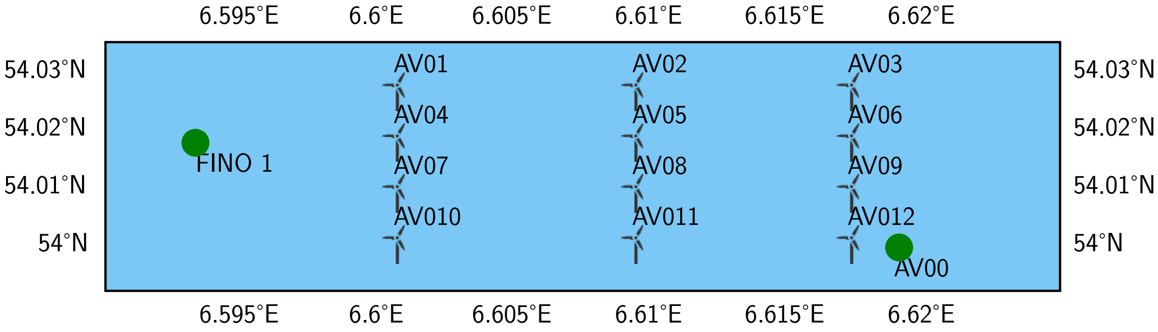

Figure 2: Location of the wind turbines (AV01-AV012), shore connection (AV00) and FINO 1 research platform at the Alpha Ventus site [15].

Constructing a wind farm like Alpha Ventus involves substantial costs, encompassing the site, hardware, and control systems. This necessitates the development of a profitable operation strategy. According to the German Renewable Energy Sources Act (EEG) 2017 and German Offshore Wind Act (WindSeeG), German wind farm operators are required to participate in the EPEX Spot market (spot market of the European Power Exchange) in Paris since 2017. The EPEX Spot market offers day-ahead and intraday trading. The EEG law was first published in 2000, and before 2017, operators received a fixed compensation based on the amount of energy produced [16, 17]. Further information is given in section 3. On the day-ahead market, electricity prices for the next day are determined by tenders, with bids having to be submitted by midday the previous day. This requires accurate wind energy forecasts from the operators, who must compensate for any discrepancies in the intraday market [18]. Our study combines the operation of Alpha Ventus with the prices of the EPEX Spot market to develop an optimal strategy for integrating an electrolyzer, considering the need for accurate forecasts of energy production and financial feasibility. Data records used in our analysis are outlined in the tab. I, including detailed turbine data and FINO 1 measurements at 10-minute intervals and DWD ICON-D2 model data at hourly intervals, aligning with the EPEX Spot market's timeframe.

Table 1: Overview of data records used in this work.

Type	Start Date	End Date	Resolution	Source
AV00-AV012	2011	2016	10 minutes	RAVE
FINO 1	2011	2023	10 minutes	RAVE
DWD ICON-D2	2023	2024	1 hour	DWD
EPEX Spot Day-Ahead	2015	2024	1 hour	EPEX Spot
EPEX Spot Intraday	2015	2024	1 hour	EPEX Spot

2.1 Modeling of Wind Data Forecast

In this study, wind speed predictions are derived from the ICON-D2 model developed by the German Weather Service (DWD). This model provides, among other things, wind speed forecasts for a height of 78 meters. The wind speed at the nacelle height of 92 meters above sea level is required for this study. A typical approach is to extrapolate wind speeds for different heights using Hellman's power law [19]. However, our study was also performed with the ICON-D2 at 127 meters and no significant differences in the results were found. Also, the turbine rotor reaches 158 meters at the top and 29 meters at the bottom, so 78 meters is a good approximation. Based on the DWD weather model, a data set is created that includes the forecast values available at 12:00 the day before, which is aligned with the requirements of the EPEX Spot day-ahead market.

Fig. 3 illustrates the accuracy of the entire dataset, comparing the measured wind data at FINO1 with the ICON-D2 model forecast, showing an interquartile range from the first to the third quartile and whiskers up to 1.5 times this range. Notably, for low wind speeds the forecast is too optimistic and for high wind speeds to pessimistic. Especially high wind speeds above 17.5 m/s were never correctly forecasted. A negative error indicates that the forecast wind speed was lower than the actual wind speed.

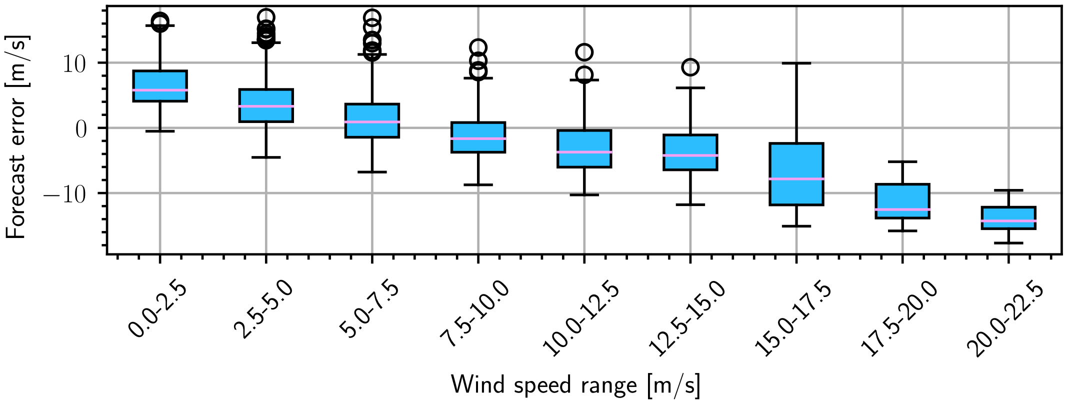

Figure 3: The accuracy of the ICON-D2 model forecast, available for the day-ahead market, compared to the measurements at the Alpha Ventus site for different wind speeds.

2.2 Simulation of Wind Farm Energy Production

The publicly available power curves of the wind turbines were also validated. This is critical because the simulation in the next step relies on these curves to estimate the power production of the wind farm. First, the measured output power of the turbines was examined in relation to the measured wind speeds, and the power curve of the wind turbines was validated. Above the nominal wind speed, the output power was found to be 5% higher than specified, which was accounted for in the power curve. Using the wind speed data from FINO 1 and the scaled power curve, we simulated the total power output of the wind farm. The wake effects of the turbines were neglected for this investigation [20]. An example of this simulation, comparing the measured power output of turbine AV04 with the simulation results, is shown in fig. 4.

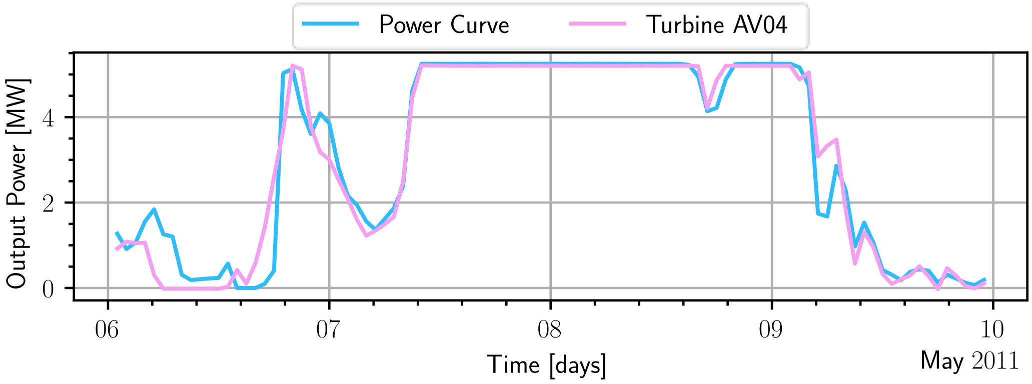

Figure 4: Comparison of the measured output power of the AV04 wind turbine with the predicted power based on wind speed measurements and the power curve.

2.3 Optimal Sizing of the Electrolyzer

According to [21], current on-site costs of about 5€ per kg of H_2 are possible with more than 3500 full load hours per year. Future projections for 2030 suggest a decrease in on-site costs to 2€ - 4€ per kg H_2, influenced by technological advances and increased operational efficiency [22, 23]. Wind data from previous years is used to evaluate full load hours. With an electrolyzer up to 30 MW, the required 3500 full load hours can be achieved (see fig. 5). However, space is an important factor for offshore applications. It will be demonstrated that even a smaller 8.6 MW electrolyzer offers a significant advantage. [24] estimates the investment cost for a 4.3 MW electrolyzer at 3.3 M€. The economic life is 20 years or 90,000 load hours, resulting in an estimated operating cost of 74€ per hour if two of these units are used. Additional costs for space on an offshore platform and maintenance are not included. With a typical efficiency of 70% [24, 25] and a specific energy requirement of 33 kWh per kg of H_2 [12], an 8.6 MW electrolyzer can produce approximately 195.16 kg of H_2 per hour. To prolong the life of the electrolyzer and ensure economic efficiency, the electrolyzer is only operated when the available power exceeds 50% of its rated power. The following analysis includes the operating cost of the electrolyzer. This investment is significantly lower than the cost of installing a wind turbine, estimated at 2 M€ per MW (including foundation), highlighting the economic advantage of electrolyzer in terms of scalability and cost-effectiveness [24, 26].

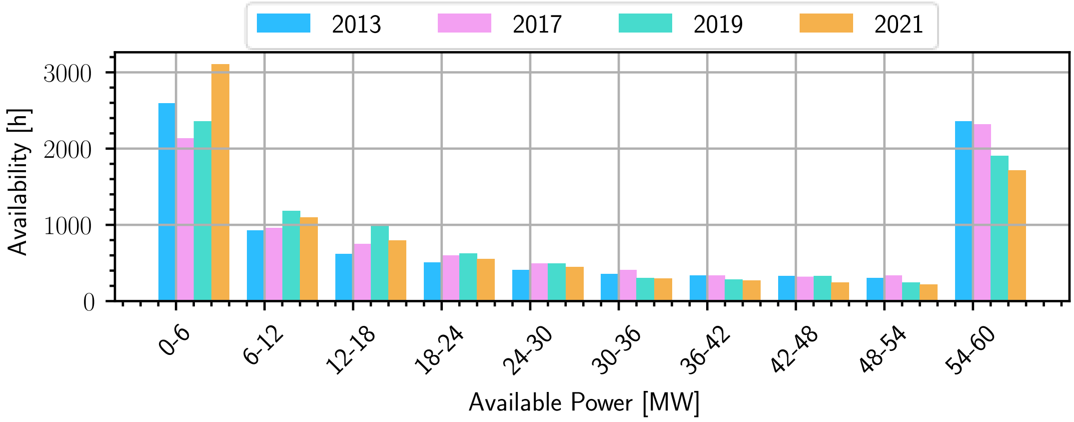

Figure 5: Duration in hours for which a certain power is available annually in the period between 2013 and 2021.

3 Energy Market Pricing and Regulatory Framework

In recent years, the original EEG-2000 has undergone several significant changes, particularly for offshore wind. The EEG-2012 and EEG-2017 laws were the most important, with the former increasing the compensation for offshore wind energy to 15 ct./kWh for 12 years. These compensation schemes remained in place until the introduction of the WindSeeG-2017, thus continuing to apply to wind farms already in operation [27]. In 2017, the WindSeeG was explicitly designed for offshore wind farms and replaced the previous EEG models. This new regulation shifted to a competitive bidding process. The construction permit for a wind farm is awarded to the operator who proposes the lowest tariff per kWh. Recent developments have seen tariffs mostly as low as 0 ct./kWh, and in 2023, permits were awarded to operators offering 0 ct./kWh and bidding for the permit, underlining the increasing market competitiveness of offshore wind [28, 29].

Three scenarios are considered for the assessment of a wind farm with an electrolyzer. All scenarios include the Alpha Ventus wind farm. The first scenario is the fixed tariff model of 15 ct./kWh for the energy produced. In the second one, the operator participates in the day-ahead EPEX Spot market based on power forecasts from the ICON-D2 model and adjusts for excess or deficit of energy production in the intraday EPEX Spot market based on wind measurements. The third scenario is similar to the second one, but the day-ahead bid is reduced by the output of the electrolyzer, and in the event of an overly optimistic forecast and consequent energy deficit, the electrolyzer would be curtailed. The capacity of the electrolyzer is specified in the following subsection. Furthermore, the scenario is evaluated with a hydrogen sales price of 5 € and 10 € per kg. These scenarios are summarized in the tab. 2:

Table 2: Overview of compared strategies.

Name	day-ahead	intraday	Hydrogen per kg	compensation per kWh
Fixed compensation	✗	✗	✗	15 ct.
EPEX Market	✓	✓	✗	✗
H_2 (10€)	(✓)*	✓	10€	✗
H_2 (5€)	(✓)*	✓	5€	✗

* Market offer reduced by the electrolyzer power

4 Results

The scope of the Alpha Ventus wind farm analysis is limited by data availability, so the focus is on the period from May 15 to September 30, 2023. The following analysis treats market data as distinct from wind forecasts. A comprehensive evaluation is ensured by comparing 2023 wind data with market data from multiple years. The profit for each strategy can be calculated as follows:

$$
\begin{array}{lclclcl}
\text{Fixed Comp.} & = & P_{prod} \cdot 15\,\text{ct./kWh} \cdot s & & & & \\
\text{EPEX Market} & = & \text{Day-Ahead}_{price} \cdot \text{ICON-D2}_{forecast} \cdot s & + & \text{Intraday}_{price} \cdot P_{diff} & & \\
\text{H2 (5€)} & = & \text{Day-Ahead}_{price} \cdot \text{ICON-D2}_{forecast} \cdot s & + & 5\text{€/kg} \cdot M_{H2} & + & \text{Intraday}_{price} \cdot P_{diff} \\
\text{H2 (10€)} & = & \text{Day-Ahead}_{price} \cdot \text{ICON-D2}_{forecast} \cdot s & + & 10\text{€/kg} \cdot M_{H2} & + & \text{Intraday}_{price} \cdot P_{diff}
\end{array}
$$

where s is the fraction of the forecast power sold, P_{prod} is the total power produced by the wind farm, P_{diff} is the energy surplus or deficit relative to the forecast, and M_{H2} is the amount of hydrogen produced. The day-ahead market offers are adjusted to account for the power consumption of the electrolyzer. In the case of an energy deficit, the electrolyzer power is reduced by up to 50% or otherwise shut down to meet the day-ahead offer. A nominal electrolyzer capacity of 8.6 MW is assumed for the analysis, with detailed discussions in the following sections.

4.1 Profit for Various Operating Strategies

Our initial investigation aims to quantify profits in different segments: fixed compensation, day-ahead market, intraday market, and hydrogen sales. Fig. 6 shows these profits, expressed in millions of euros, compared to the volume of forecasted energy transacted in the day-ahead market. In the fixed compensation scenario, a proportional increase in profit relative to the volume of energy sold is observed, highlighting a linear relationship. Notably, the absence of energy sales (0%) results in zero compensation. The day-ahead market scenario similarly shows higher profit with increased energy sales, but when compared, fixed compensation consistently outperforms day-ahead market returns.

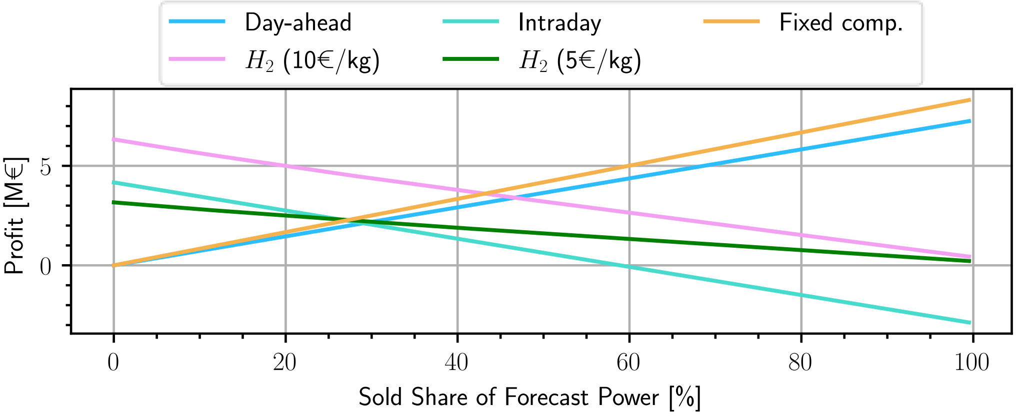

Figure 6: Breakdown of the profit categories corresponding to the different operating approaches, depending on the forecast energy sales. The electrolyzer has a nominal power of 8.6 MW.

The accuracy of wind forecasts is critical, as inaccuracies may require energy to be bought back in the intraday market. Conversely, conservative day-ahead trading can result in excess energy that must also be sold in the intraday market. It's important to note that in scenarios where intraday prices fall into negative territory, no transactions occur, resulting in a potential wind farm curtailment.

In addition, profit trajectories for hydrogen electrolysis are included, although the day-ahead curve doesn't show the adjusted bidding strategy. Particularly, with a hydrogen price of 10 €, the profit in the intraday market is increased. When participating heavily in the day-ahead market, the electrolyzer often has to be curtailed to meet the offer, leading to a decrease in profit. However, the loss is significantly reduced due to the lesser need to buy energy on the intraday market. The cost of operation is also factored into the analysis by deducting from the profit for each operation hour based on the acquisition cost specified in section 2.3.

By combining these profit categories, the total profit for each strategy can be calculated and presented in relation to the share of forecasted power traded in the day-ahead market. The results for the three strategies and two hydrogen prices are shown in fig. 7, and the revenues for several years are shown in the tab. 3. The profit of the fixed compensation case is identical to fig. 6 and leads to the highest profit. However, this compensation model is only available for older wind farms already in operation and will not be discussed further. The electrolyzer with a capacity of 8.6 MW leads to an increase in revenue of 6% compared to the EPEX market strategy in 2023. If the price of hydrogen is increased to 10€, the revenue can be further increased by 44%. Interestingly, the highest profit in this case can be achieved if the operator only participates in the intraday market. The profit increases for the EPEX market strategy and a hydrogen price of 5€ if the operator participates strongly in the day-ahead market. The analysis of different years showed that it is always advantageous to participate only in the intraday market when hydrogen prices are high.

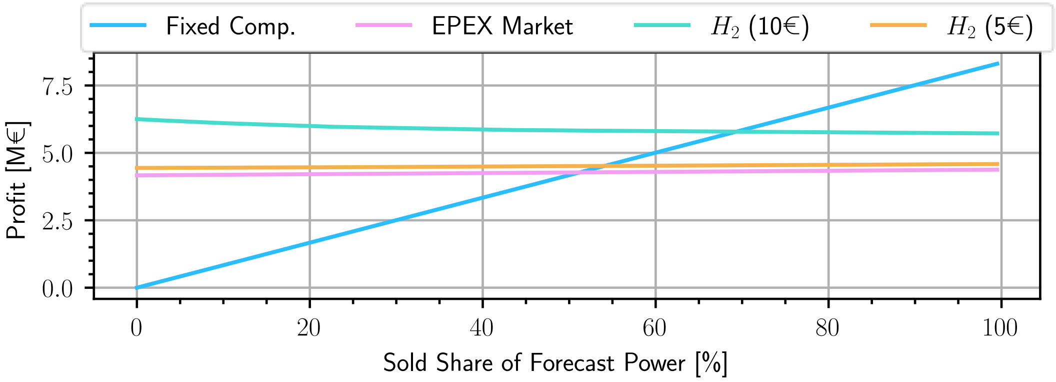

Figure 7: Total profit for the strategies presented in table 2 based on the traded share of forecasted energy production at the day-ahead market in 2023.

Next, it is essential to check how the recent market price increase affects this result [30]. Market data from previous years is used, along with the same market data, to determine if there is also an increase in profits when hydrogen is produced. Tab. 3 shows the profits between 2016 and 2023. In the years before 2021, the revenue could be increased up to 65% by including an electrolyzer in the wind farm, but with the increase in energy prices in 2021, it was more profitable to sell the energy on the EPEX market compared to operating an electrolyzer. In 2023, energy prices on the EPEX Spot market dropped significantly, making it profitable to operate the electrolyzer. However, the potential coupling between a significant increase in energy prices and the price of hydrogen is not considered here.

Table 3: Annual profit for each operating strategy.

Year	**Fixed Comp. [€]**	**EPEX Market [€]**	**H_2(10€) [€]**	**H_2(5€) [€]**	**Profit [%]***
2016	8,348,958	1,703,350	4,622,004	2,810,713.6	65
2017	8,348,958	1,899,393	4,843,761	3,032,470.7	60
2018	8,348,958	3,134,680	5,546,668	3,735,378.1	19
2019	8,348,958	2,399,823	5,121,187	3,309,896.6	38
2020	8,348,958	1,956,584	4,876,188	3,064,898.0	57
2021	8,348,958	5,858,673	6,990,598	5,856,035.3	-0

2022	8,348,958	17,026,089	15,804,423	14,669,859.8	-14
2023	8,348,958	4,379,238	6,329,219	4,634,849.4	6

* Profit of the H_2 (5 €) strategy compared to the EPEX Market strategy

4.2 Optimal Rated Power of the Electrolyzer

Finally, the influence of the electrolyzer's nominal power on the profit is studied. Fig. 8 shows four different hydrogen price scenarios and the revenues for different nominal electrolyzer capacities at the Alpha Ventus wind farm. In the case of 15€ per kg, the highest profit can be achieved. However, it is beneficial to have a higher amount of installed wind power than the nominal power of the electrolyzer to increase the profit. In this case, the maximum is at an installed power of 46.5 MW and the wind farm has a rated power of 60 MW. This is true for all curves except for 2€, where the maximum is at a capacity of 0 MW. For a hydrogen price of 10€ and 5€, the revenue also increases with the nominal power of the electrolyzer, but the increase is much smaller, and for a price of 2€, the revenue decreases compared to not using an electrolyzer due to the operating costs of the electrolyzer. For larger electrolyzer sizes, the space requirement also increases, leading to additional costs for building offshore platforms, which are not included in this graph. These costs are difficult to estimate as they are highly dependent on local conditions. It can also be observed that a small electrolyzer leads to the most significant increase in profit, as it can compensate for forecast errors by curtailment.

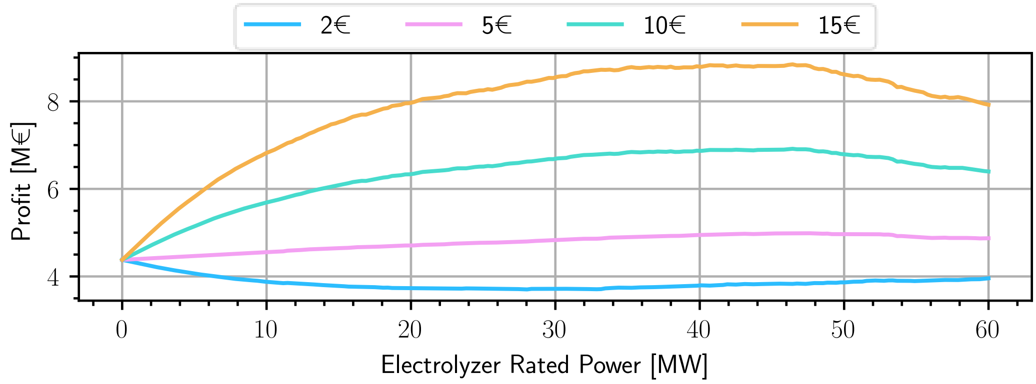

Figure 8: Total profit for different hydrogen prices in relation to the nominal capacity of the electrolyzer at the Alpha Ventus wind farm.

4.3 Consequences for the Regulatory Framework

Since the WindSeeG-2018, offshore sites have been categorized into two groups: those for power generation only and others for various power generation purposes (SoEnergieV-2021), including hydrogen production. However, this distinction leads to a curtailment of wind energy during periods of negative EPEX Spot market prices, as energy production during these periods results in losses for the operator. With ambitious government targets for renewable energy expansion, the frequency of negative prices and consequent curtailment is likely to increase. This scenario requires regulatory adjustments.

It is proposed that wind farm operators be allowed to integrate a modestly sized electrolyzer, for example, one with a capacity equivalent to up to 15% of the wind farm's rated power. A larger electrolyzer can further increase the profit, but it also delivers less power to the grid, which is in conflict with the decarbonization of the energy sector. This approach has several benefits. First, it enables sector transformation by ensuring the availability of hydrogen. Second, it reduces the need to curtail wind energy production, especially when selling electricity is not financially feasible due to negative spot market prices, as the excess power can be used for electrolysis. Finally, since sites designed for alternative energy harvesting methods are often located far from shore, applying our strategy to wind farms for energy production can significantly reduce the transportation costs associated with hydrogen.

5 Advantages of DC

Distance is a limiting factor for high power transmission. Reactive current increases with distance, reducing the amount of active power that can be transmitted. The maximum length of a typical 220 kV cable is about 120 km [19, 31]. At this distance, the power transmitted is purely reactive. To reduce these effects, the frequency and, thus, the reactive power required can be reduced [32]. Besides low-frequency AC, there is an extreme case of DC transmission where no reactive power is required during continuous operation [33]. As there are no DC wind farms in operation, it isn't easy to estimate the exact cost compared to an AC system, but in [34], it was concluded that a DC grid for offshore applications could lead to cost savings of up to 20%.

The DC grid also has the advantage of higher efficiency during operation. In [10], the efficiency advantage is shown based on the grid's proportion of AC or DC devices. For offshore wind farm applications with type 4 turbines, HVDC connection, and electrolysis, the share of DC is 100% because the wind turbines need to rectify the AC generator voltage to produce a constant frequency [19]. A study of medium-voltage land-based systems has shown that the use of DC for the grid can reduce energy losses from about 11.5% to 4.5% [10, 34, 35], a reduction of 61%. In [36], the losses of a wind farm AC collector grid were estimated to be 2.96%. Combined with the data of the tab. 3 a reduction in profit of over 110,000€ in the period of 4.5 months can be estimated due to AC grid losses. The increase in efficiency of DC has the potential to reduce losses to less than 43,000 €. The proposed DC collector grid system also offers significant advantages over AC systems, such as eliminating reactive power and skin effect, resulting in reduced cable diameter and copper usage. In addition, using a two-wire DC system instead of a three-wire AC system provides significant material cost savings. DC-DC converters, which operate at higher frequencies than typical AC transformers, significantly reduce size and weight, a critical consideration for offshore platforms [37]. The slow development is because

DC protection technology is challenging, and many components are unavailable for DC systems [38].

6 Conclusion

This paper presents the economic benefits of integrating hydrogen production into an offshore DC wind farm, using the Alpha Ventus wind farm as a reference model. Our analysis focused on the economic feasibility of this integration under different market scenarios and using the ICON-D2 model for wind speed forecasting. Our study underscores the importance of accurate wind forecasting models and strategic market participation to optimize profitability. Key findings include:

1. **Benefits of DC:** DC is the state-of-the-art solution to increase transmission efficiency over distance. It can potentially reduce the collector grid investment by up to 20% compared to AC in offshore applications. DC collector grids also reduce energy losses by approximately 60%.
2. **Profitability of Hydrogen Production:** At current market prices for energy, hydrogen production at 5 € per kg H_2 leads to an increase in revenue from 19% to 65% between 2016 and 2020. Due to the high energy prices in the following years, 2021 and 2022, hydrogen production is only profitable at higher hydrogen prices. In 2023, a 6% increase in revenue was found.
3. **Adapting the regulatory framework:** The current legal framework poses the risk of curtailing renewable energies. Permitting the integration of an electrolyzer can solve this problem.
4. **Electrolyzer Operation Efficiency:** The electrolyzer's nominal power was optimal when the wind farm's power capacity was 30% greater than the power of the electrolyzer. This ensures a higher probability of the electrolyzer running at full load, thereby maximizing hydrogen production.
5. **Forecast Accuracy and Market Participation:** Inaccuracies in wind forecasts significantly impacted market participation strategies. While conservative forecasts often resulted in excess energy production (sold into the intraday market), the profits from these sales were lower than those from day-ahead market sales. However, when market participation is high, a significant amount of energy must be purchased during intraday trading, but operating in the day-ahead market is still advantageous.
6. **Profitability Analysis:** The fixed compensation model generally resulted in higher profits than the day-ahead and intraday market strategies but is unavailable for newly built wind farms. This is consistent with the high initial construction costs of offshore wind projects.

Future research should focus on long-term data analysis to further validate the economics and efficiency of hydrogen production in offshore wind environments. In addition, advances in wind prediction models and electrolyzer technologies could provide deeper insights into the optimization of wind farms. In conclusion, this work contributes to the growing body of knowledge on renewable energy solutions, particularly in the global shift towards cleaner, more sustainable energy systems. The Alpha Ventus wind farm case study results provide valuable insights into the practical and economic aspects of integrating hydrogen production into offshore wind farms, highlighting both the challenges and opportunities of this approach.

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