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Vision of Offshore Energy Hub at Faroe Islands: The Market Equilibrium Impact

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ABSTRACT

This study examines the integration of an offshore wind farm and green hydrogen production as a strategy to enhance the Faroe Islands' energy independence and reduce its carbon footprint. Utilizing the EnergyPLAN tool and market economic simulations, including Levelized Cost of Hydrogen and Net Present Value calculations, the research evaluates the economic viability and environmental impact of transitioning to renewable energy sources by 2030. The analysis explores various scenarios, ranging from dedicated offshore wind for in-turbine hydrogen production to platform-based electricity and hydrogen distribution. Results indicate that integrating offshore wind with green hydrogen production can significantly reduce CO_2 emissions and dependency on imported fossil fuels. However, financial viability hinges on supportive mechanisms such as investment subsidies. The study's findings suggest that achieving economic feasibility requires strategic policy frameworks. This research contributes to the discourse on sustainable energy planning by offering insights into the dynamics of system integration, market economic simulations, and the role of support mechanisms in facilitating the green transition.

Keywords

Faroe Islands;
Offshore wind;
Hydrogen;
EnergyPLAN;
Market economic simulations

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1. Introduction

The urgent need to mitigate climate change and transition to a low-carbon economy has spurred the exploration of innovative and sustainable energy solutions. Among these solutions, the integration of offshore wind farms and green hydrogen (H_2) production holds potential. Offshore wind farms, with immense renewable energy capacity and steadily declining cost, offer a source of clean electricity generation [1,2]. At the same time green H_2 produced through electrolysis powered by renewable energy, serves as a versatile and emissions-limited energy carrier with the potential to decarbonize various sectors, including transportation and industry [3].

In this study, the focus is on the Faroe Islands, where the energy system is heavily reliant on imported fossil fuels for their energy needs. To reduce their carbon footprint and increase energy independence, the government has set a target for producing the country's land-use electricity and transportation from renewable sources by 2030, preliminary coming from onshore wind [4]. Furthermore, there is an aim of having ammonia (NH_3) driven vessels covering 11% of the maritime sector. To minimize the dependency on oil, an integration of offshore wind producing green H_2 can be a viable solution,

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where the H_2 is converted to NH_3 to be used for the maritime sector. The success of this incorporation relies not only on the integration of offshore wind and green H_2 technologies but also on the political investment as support mechanisms. These mechanisms can incentivize investment, mitigate financial risks, and drive technological advancements [5–12].

Therefore, understanding support mechanisms, such as investment subsidies and financing mechanisms, among others, are crucial in maximizing the potential of offshore wind. By evaluating the energy system using the EnergyPLAN tool [13–15] with an integrated green H_2 production and utilizing market economic simulations (Levelized Cost of Hydrogen (LCoH) and Net Present Value (NPV)), it is possible to assess the economic viability [9,16,17]. The evaluations in this article can be used to guide strategic decision-making and shape the transition to a sustainable energy future for the Faroe Islands. Thus, emphasizing the integration of renewable energy sources and H_2 production as key components of their energy landscape. In the scope of this study, the reconversion of H_2 to electricity is not examined. Rather, the emphasis is on harnessing offshore wind energy for NH_3 production intended for the maritime sector.

By studying the details of the energy system in the Faroe Islands, it is possible to gather insights into the dynamics and interplay of energy policies, market economic simulations, and sustainable integration strategies. The learnings from the Faroe Islands, particularly in the realm of offshore wind and H_2 production, provide valuable insights. These findings can potentially be scaled and adapted to inform decisions and strategies in larger regions, thereby facilitating the navigation of the transition to a more sustainable and resilient energy future for these areas.

In this paper, the Faroe Islands is classified as an Offshore Energy Hub based on its location and capability to manage diverse energy forms. This encompasses handling inputs such as electricity, oil, and district heating demand, while producing outputs, e.g., electricity and heat for private households as well as for the industry and the transportation sector. Essentially, the Faroe Islands function as a central point for collecting and distributing various energy sources and can therefore be acting as a prototype for large-scale Offshore Energy Hubs.

Thus, this paper addresses the following research questions to evaluate if offshore wind can be integrated into the Faroese Islands' energy system and if learnings can be adapted to large-scale Offshore Energy Hubs. The research questions are:

1. How will uncertainties in regulations impact decision making?
2. Under which market economic simulations can offshore energy in the Faroe Islands be feasible?
3. Can the learnings be used to assess larger regions considering Offshore Energy Hubs?

By answering these questions, the research aims to explore the Faroe Islands' energy system and if it is feasible to incorporate H_2 and NH_3 production. Furthermore, the aim is to investigate if this study case can be a representative microcosm for large-scale Offshore Energy Hubs, drawing insights into the dynamics of energy policies, market economic simulations, and sustainable integration strategies.

Previous studies have explored the advantages of integrating green H_2 into Offshore Energy Hubs [18–21] and others have investigated the impact of reaching 100% land-used renewable power system by 2030 at the Faroe Islands [17,22,23]. Furthermore, studies have investigated the impact of modeling renewable energy on islands during the transition towards sustainable and renewable energy infrastructures [9,12,24–27]. Research has also been directed towards exploring marine energy projects and transitioning to a 100% renewable energy system [8–10,23,28]. As well as studies have investigated the combination of offshore wind power production linked to H_2 and NH_3. According to the sources, then H_2 and NH_3 from renewable energy can serve as complementary energy carriers, aiding in the decarbonization of economic sectors where direct electrification is not the most optimum approach [20,21,29]. However, according to the Faroese Environment Agency's Energy Department, exploring renewables and NH_3 integration into the energy system of the Faroe Islands is in the initial phase. Therefore, this article is to enhance the understanding of the market impact by implementing an offshore wind farm at the Faroe Islands and thereby enrich the scientific literature by providing a detailed case study of the Faroe Islands as a prototype for large-scale Offshore Energy Hubs. This underlines the interplay between technological solutions, economic feasibility, and policy frameworks. It thus can equip the scientific researchers, policymakers, and investors with insights and evidence-based strategies for advancing a transition to a low-carbon, sustainable energy future for the Faroe Islands.

This paper is organized into four main sections: firstly, section 2 investigates the methods, which encompass three primary tools to assess the economic evaluation and impact of H_2 integration into the energy system of the Faroe Islands. The Subsidy Clustering is intended for addressing regulatory uncertainties, EnergyPLAN for simulating market economic scenarios, and lastly LCoH and NPV calculations for assessing economic feasibility. The results section (section 3) presents the findings from these methodologies, addressing the first two research questions mentioned above. This will be elaborated in a discussion section, also exploring the broader implications and the potential application of these insights to larger regional contexts to assess research question three (section 4). The responses to the three research questions will be answered in a concluding section (section 5).

2. Methods: simulating H_2 production in the Faroe Islands

This section outlines the processes and sources from which the data and insights are derived. The main data for the analyses comes from the Faroese Environment Agency's Energy Department, as well as from the Department of Sustainability and Planning of Aalborg University, Denmark, the latter being the creator of EnergyPLAN. This section specifies the methodology for clustering support mechanisms (section 2.1), followed by the approach of EnergyPLAN (section 2.2) and lastly leveraging LCoH and NPV for economic evaluations (section 2.3).

2.1 Methodology for evaluating subsidy mechanisms

In this study, subsidy mechanisms for offshore wind and green H_2 production were categorized. A subsidy mechanism is a financial or regulatory support system designed to incentivize the development, deployment, and operation of renewable projects [7,8,30,31]. Subsidy mechanisms can take various forms and are often implemented by governments, investors, or relevant authorities to accelerate the growth of renewable energy sources. These mechanisms aim to make renewable energy sources more financially viable, competitive with fossil energy sources, and conducive to achieve renewable energy targets. For this analysis, various attributes of each subsidy categorization were considered to identify groupings with similar characteristics (see Figure 1) [32–39]. The categorization process involved analyzing features to identify and ensure distinct subsidy categories. This framework facilitated an

Figure 1: Illustration of support mechanisms divided into seven segments

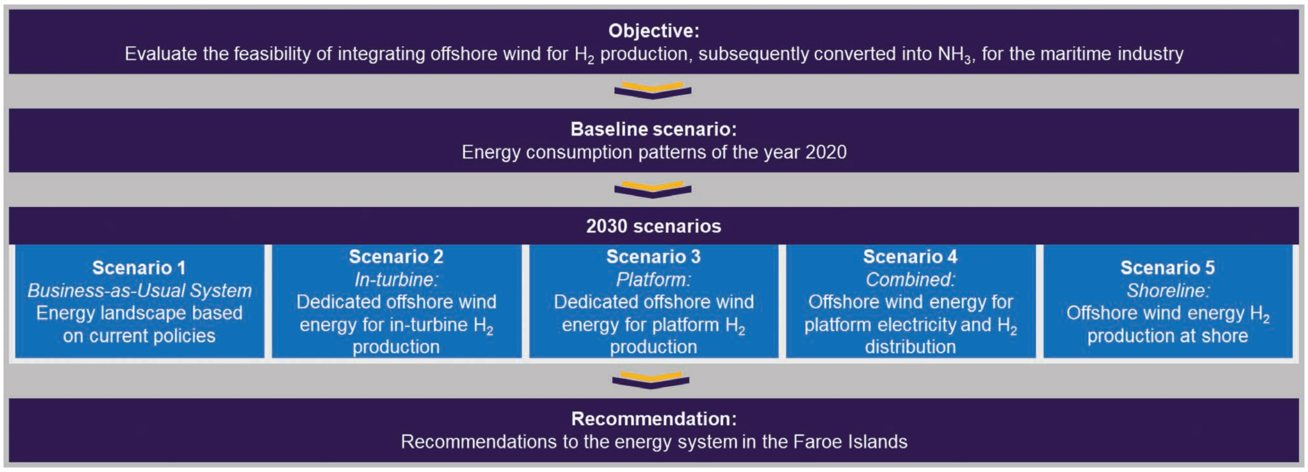


Figure 2: An overview of energy system scenarios analyzed for the Faroe Island's energy system

analysis of the support mechanisms available for offshore energy projects, utilized in section 3.

2.2 Approach to scenario modeling using EnergyPLAN

EnergyPLAN is an advanced energy system analysis tool [13]. It is used, in this paper, to model different energy system scenarios of the Faroe Islands and the related energy consequences. The main purpose of this analysis is to assist the design of the renewable energy systems utilizing offshore wind. By analyzing the technical and economic dimensions of different system designs, it is possible to determine the most sustainable and cost-effective energy system. The approach and scenarios are illustrated in Figure 2.

As the primary objective of this paper is to evaluate the feasibility of harnessing offshore wind energy for H_2 production, subsequently converted into NH_3 for the maritime industry in the Faroe Islands, distinctive systems have been determined. The initial system, termed the 'Baseline Scenario' in Figure 2, is predicated upon the energy consumption patterns of the year 2020. Scenario 1 is designated as the 'Business-as-Usual System', which projects the energy landscape for the year 2030, based on current policies. This includes all land-used electricity as well as transportation with the aim of being covered by renewable energy. It is expected that all land-used transportation, including vehicles and truck are electrified as well as electrification of individual heat pumps. Scenario 2 to 5 adds on this with different placement of H_2 production for conversion to NH_3 to substitute part of the diesel driven vessel fleet. Scenarios 2 and 3 utilize purely offshore wind energy for H_2 production. The distinction between these scenarios is in the location of the electrolyzer for H_2 production. It involves either situating the electrolyzer directly at the wind turbine (Scenario 2) or deploying it on a separate offshore platform (Scenario 3). In Scenario 4, the offshore wind farm serves a dual purpose by facilitating both electricity and H_2 production. The electrolyzer is positioned on the offshore platform, enabling the transportation of both electricity and H_2 to the mainland from the platform. Conversely, Scenario 5 places the electrolyzer at shore, with only electricity being conveyed from the offshore wind farm. At the connection point it can then be used either for electricity or H_2 production.

Data for the scenarios originate from both the Department of Sustainability and Planning of Aalborg University, Denmark and the Faroese Environment Agency's Energy Department and can be seen in Table 1. It is assumed that oil used for transportation is less efficient than electrified transportation and therefore the total energy demand will decline compared to the Baseline Scenario.

2.3 Method for economic analysis via Levelized Cost of Hydrogen and Net Present Value calculations

LCoH is an economic assessment calculating the levelized cost of producing H_2. It considers all the costs (like startup costs, running costs, and maintenance) over the project's lifetime and divides them by the total amount of H_2 produced during that period [3]. See equation (1) for the LCoH calculation. LCoH is particularly useful in assessing the economic viability of different H_2 production to explore the potential of H_2 as a clean energy carrier.

Table 1: Input parameters for scenario modeling using EnergyPLAN.

Inputs parameters	Baseline Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Electricity Demand (GWh/year)	400	675	675	675	675	675
Heating Demand (GWh/year)	615	466 (Including individual heat pumps)	466 (Including individual heat pumps)	466 (Including individual heat pumps)	466 (Including individual heat pumps)	466 (Including individual heat pumps)
Diesel and petrol supply (GWh/year)	1,180	750	668	668	668	668
Renewable energy source supply without offshore wind (GWh/year)	83	1,011	1,093-1,124[1)]	1,093-1,124[1)]	1,093-1,124[1)]	1,093-1,124[1)]
Offshore wind energy supply (GWh/year)	0	0	383-417[1,2)]	383-417[1,2)]	383-417[1,2)]	383-417[1,2)]
Ammonia (NH_3) production (GWh/year)	N/A	N/A	313	313	313	313
CO_2 price (€/t CO_2)[3)]	70	108	108	108	108	108

[1)]Depending on the system setup

[2)]Assuming an ~80 MW wind farm with ~59% capacity factor

[3)]Prices provided by the Faroese Environment Agency's Energy Department

Table 2: Input parameters for estimating LCoH and NPV

Inputs parameters	Wind farm	Electrolyzer setup sub-scenario 'A'	Electrolyzer setup sub-scenario 'B'
Lifetime (years)	30	30	30
Investment over lifetime (million €)	105-132*	136 (1.7 per MW) [41][3]	40 (0.55 per MW) [3]
Annual O&M per % of capital expenses	9	1.5 to 3* [40]	1.5 to 3* [40]
Size of wind farm (MW)	~80		
Yearly H_2 production (GWh)		358	358
Inflation (%)	2 [42]	2 [43]	2 [37]
Discount rate (%)	6 [42]	6 [42]	6 [42]
Corporate tax rate (%)	22 [43]	22 [43]	22 [43]
H_2 prices (€/kg H_2)	Prices from ENTSOG TYNDP 2022 - with linear forecasting [44]		

*Depending on system setup (Scenario 2-5)

$$\text{LCoH}\left(\frac{€}{\text{kg}}\right) = \frac{\text{Present value of all } \textit{lifetime} \text{ Cost}}{\text{Present value of all } \textit{lifetime} \text{ Park Hydrogen Production in kg}} \quad (1)$$

NPV assesses the profitability of a project by comparing the present value of expected revenue streams to the initial investment and running cost over the lifetime (n) [40]. By discounting future cash inflows and outflows back to their present values and then subtracting the initial investment, NPV indicates the expected net value or profitability of a project [9,16,17]. See equation (2) for the NPV calculation.

$$NPV = \sum_{n}^{N} \frac{\left(H_2\ price@year\ n \times Net\ Annual\ Hydrogen\ Production@year\ n\right)}{\left(1+discount\ rate\right)^n} - \sum_{n}^{N} \frac{cost@year\ n}{\left(1+discount\ rate\right)^n} \quad (2)$$

A positive NPV suggests that the project can yield a return above the discount rate, while a negative NPV signals a return less than the discount rate, guiding investment decisions. See all inputs parameters for the calculations in Table 2. Diverse sources present varied cost estimates for electrolyzers. Accordingly, this study incorporates an analysis of both high-cost (sub-scenario 'A') [41] and low-cost (sub-scenario

'B') [3] for electrolyzers, where the results are detailed in Section 3.3.

In this study, the NPV is used to determine if the investment in the offshore wind farm is feasible on pure market conditions or if a support mechanism is needed for the investor to minimum break-even, building on section 2.1.

Several assumptions and simplifications were incorporated into the calculations. For instance, the annual H_2 production estimation was calculated on the anticipated location of the Faroese wind farm, as provided by the Faroese Environment Agency's Energy Department. The wind distribution data for this specific location was sourced from the ConWx-Hindcast database [45]. From this database, it is possible to retrieve power production and weather-based forecasting for a specific location. Additionally, it is assumed that the investment for the wind farm includes the full setup as wind turbines, foundations, installation, cabling, pipes, and substation.

3. Results: Wind energy's impact on H_2 production in the Faroe Islands' energy system

Having employed the methodologies descripted in section 2, this section explains the findings derived from each approach. These results provide tangible data and insights to address the research questions mentioned earlier, paving the way to the discussion in section 4 and conclusion in section 5.

3.1 Results of subsidy mechanisms and their impact

The segmentation analysis has yielded various categories for support mechanisms in the context of investing renewable energy. These categories encompass different mechanisms tailored to specific aspects of renewable project development and operation, as described in section 2.1.

For this research, the key design parameters of the European Hydrogen Bank (EHB) support are applied for section 3.3. The scope of the EHB is to enable scaling of H_2 production and supporting the development of the H_2 supply chain. The European Commission has proposed to allocate a level of fixed price payment per kg of produced H_2 for a maximum of 10 years [37]. Given the description of the EHB's goals and functions, it is most apt to categorize the mechanisms of EHB support system as part of the *'Investment Subsidy'* and *'Regulatory Subsidies'*, as seen in Figure 3.

In this research, the needed premium is determined as a factor on top on the H_2 prices to establish a financially viable model for developers. The determination will be calculated upon data shown in Table 2, in conjunction with the design parameters proposed by the European Commission [33].

3.2 Simulation and scenario analysis using EnergyPLAN

Utilizing the EnergyPLAN model [13], the simulation of the Faroe Islands' potential offshore wind and H_2 production can be seen in Table 3. The Baseline Scenario demonstrated a considerable reliance on fossil energy sources. In

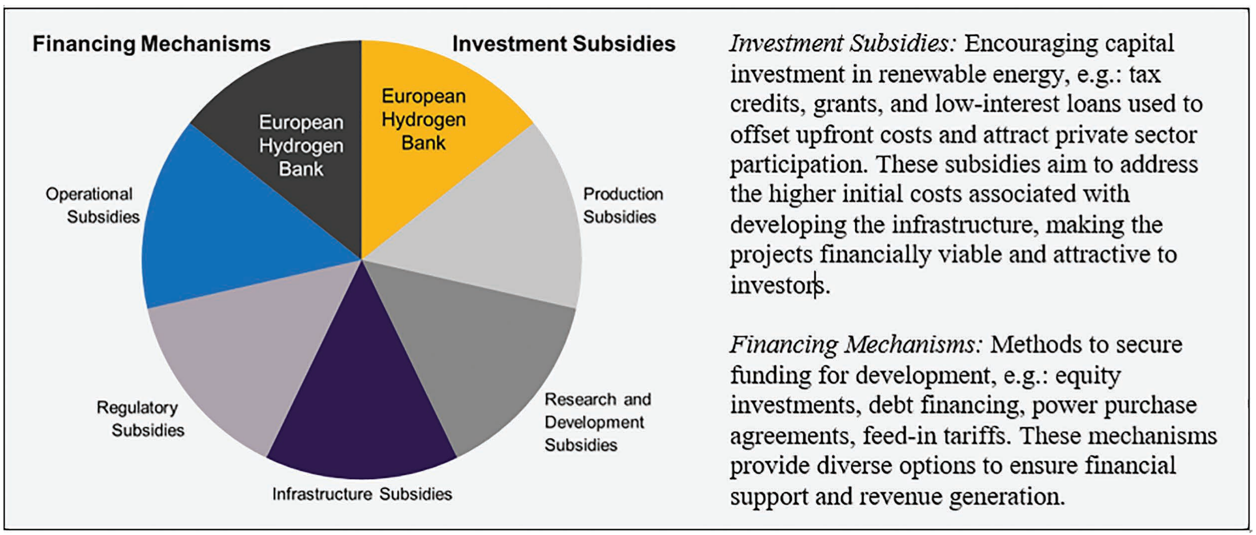
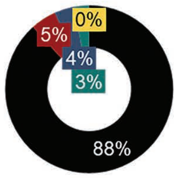
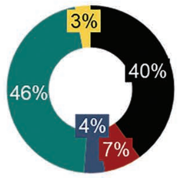
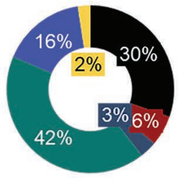
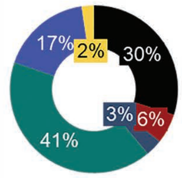
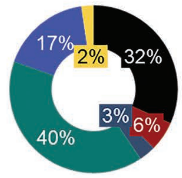
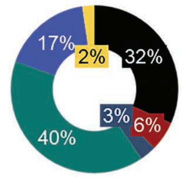


Figure 3: Segmentation of energy subsidies and financial mechanisms used to support renewable energy projects. The mechanisms of EHB have been applied in the analysis

Table 3: Results of the EnergyPLAN assessment

Energy	Scenario Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Scenario description	Energy landscape based on current policies	Dedicated offshore wind energy for in-turbine H_2 production	Dedicated offshore wind energy for platform H_2 production	Offshore wind energy for platform electricity and H_2 distribution	Offshore wind energy for platform electricity and H_2 distribution	Offshore wind energy H_2 production at shore
						
System cost (mEUR p.a.)	288	234	282-291	285-294	278-287	273-281
CO_2 emission (mEUR)	48.5	23.5	22.1	22.1	23.5	23.5
Primary energy demand (GWh/year)	2,881	1,915	2,361	2,396	2,419	2,419

contrast, Scenario 1 illustrated advancements in sustainable energy adoption but fell short of transformation in the shipping sector. When contrasting the Baseline Scenario with Scenario 1, the assumption is that fossil fueled transportation is less efficient than electrified options, leading to a reduced total energy consumption in Scenario 1.

A paradigm shift is evident in Scenario 2 to 5 (see Table 3). In Scenario 2 and 3, oil consumption drops to approximately 715 GWh. Onshore wind is with 990 GWh, where offshore wind accounts for 383 to 417 GWh, depending on the electrolyzer setup. Both Scenario 2 and 3, utilize offshore wind for only H_2 production. However, Scenario 2 requires fewer electrical cables compared to Scenario 3, as the need is only within the turbine. This leads to an overall higher efficiency for Scenario 2 than for Scenario 3. Consequently, the two scenarios demand different offshore wind farm sizes to yield the same volume of H_2 to be converted to NH_3. This result in a smaller offshore wind farm in Scenario 2 to match the NH_3 output of the offshore wind farm in Scenario 3.

Lastly, Scenario 4 and 5 reveals a different energy consumption pattern. Compared to Scenario 2 and 3, these scenarios require an onshore wind of 965 GWh (reduction of 2.5%) to create the same energy system. This is because offshore wind can partially replace onshore electricity production, thereby reducing the need for onshore wind capacity. On the other hand, scenario 4 requires building double infrastructure for electricity and H_2 transport, which has a negative impact on the cost associated with this scenario.

Across Scenario 2 to 5, the transformative potential of renewable energy, especially offshore wind, in the Faroe Islands' energy landscape is evident. The results underscore the shift from traditional to green energy sources, emphasizing the importance of offshore wind in achieving the goal of converting green H_2 to NH_3 to be used for NH_3 driven vessels. As seen in Table 3, converting offshore wind to H_2 and then to NH_3 increases the total energy need compared to Scenario 1. This is due to more conversion steps in the process of converting offshore wind to H_2 and afterwards to NH_3, compared to using fossil fuel driven vessels.

Moreover, as Table 3 outlines, the assessment of the Baseline Scenario revealed an annual cumulative system cost of 288 million euro (mEUR) and a CO_2 emission of 49 mEUR. Looking at trajectory of Scenario 1, it results in a cost decrease to 234 mEUR and CO_2 emissions dropping. The reduction in costs between these two scenarios can be attributed to the diminished reliance on oil in the energy mix.

For Scenario 2, the yearly cost is increased to 282–291 mEUR, depending on the electrolyzer cost [3,41]. Scenario 3 close to mirrors these results, with a slightly larger offshore wind farm to cover the same NH_3 demand. For Scenario 3, the size of the windfarm increases, requiring approximately 80 MW, whereas Scenario 2 necessitates in the region of 74 MW. As mentioned before, this is because the in-turbine model (Scenario 2) has limited energy loss via electricity cables. Lastly, Scenario 4 displayed a system cost of 278–287 mEUR and Scenario 5 a cost of 273–281 mEUR. Here the ranges in system cost are also due to difference in electrolyzer cost [3,41]. Notable advantages for Scenario 5 are the reduced annual expenses, stemming from the absence of H_2 pipelines and lower operational expenses (OPEX). The lower OPEX is largely because of fewer maintenance challenges; there is no need for service vessels, and service technicians are not affected by weather downtime compared to offshore service.

3.3 Economic feasibility through Levelized Cost of Hydrogen and Net Present Value Assessments

Table 4 details the economic analyses for various electrolyzer setups. In the scenario where the electrolyzer has the highest cost (1.7 mEUR/MW [35] - sub-scenario 'A' for all scenarios), scenario 2A results in a noteworthy negative NPV. Scenario 3A presents an even more negative NPV. The LCoH in €/kg ranges between 3.9 and 4.0 for Scenario 2A and 3A. With reduced electrolyzer costs (0.55 mEUR/MW [3] - sub-scenario 'B' across all scenarios), an improvement is evident, although the NPV remains negative for both scenario 2B and 3B.

Scenario 4A yields the most negative NPV, and even with a decrease in the electrolyzer cost (as seen in scenario 4B), the LCoH and NPV do not improve compared to those in sub-scenarios for Scenarios 2 and 3.

In Scenarios 5A and 5B, the same trend in NPV values is apparent, driven by electrolyzer cost. Similar observations apply to the corresponding LCoH metric. These scenarios result in less negative NPVs and lower LCoH variables compared to other sub-scenarios. This is not only attributed to reduced costs but also to the benefit of utilizing energy from the offshore wind farm for both electricity and H_2 production. With an efficient management system, it is possible to maximize revenue by generating electricity when its prices surpass those of H_2, and vice versa. Although the dual production feature, is also present in Scenario 4A and 4B, this setup burdens the developer with the cost of both H_2 pipelines and electrical cables, in addition to higher OPEX expenses.

As mentioned in section 2.3, a negative NPV signals a return less than the discount rate and will therefore not be an economical investment for the developer. Thus, the integration of supportive frameworks becomes important. Utilizing a mechanism akin to the EHB setup and calculated as a factor applied to the H_2 prices, the high-cost framework necessitates H_2 price multipliers ranging from 2.8 to 3.7 to reach an NPV break-even point. Conversely, the low-cost scenario factors are ranging from 1.9 to 2.5 to achieve a similar economic parity. All the results can be seen in Table 4.

As mentioned above, the requisite premium to establish a financially viable model is calculated as a factor. In the terms and conditions reported by the Innovation Fund Auction, a max fixed premium of 4.50 €/kg for H_2 produced is the aim of the EHB setup [46]. The results of this approach can be seen in Table 5. All scenarios with the low-cost electrolyser demonstrate a positive NPV. Conversely, for all scenarios with the high-cost electrolyser, the premium will be insufficient to achieve a sustainable outcome.

Table 4. Results of Economic Analysis via Levelized Cost of Hydrogen and Net Present Value Calculations

Results	Scenario 2A	Scenario 2B	Scenario 3A	Scenario 3B	Scenario 4A	Scenario 4B	Scenario 5A	Scenario 5B
Source for estimated prices (€/kg)	ENTSOG TYNDP 2022 Scenario [44]		ENTSOG TYNDP 2022 Scenario [44]		ENTSOG TYNDP 2022 Scenario [44]		ENTSOG TYNDP 2022 Scenario [44]	
NPV (mEUR)*	−229	−97	−241	−108	−299	−166	−201	−92
LCoH (€/kg)*	3.9	2.7	4	2.8	4.6	3.5	3.8	2.9
Price factor to break even	3.3	2.0	3.4	2.1	3.7	2.5	2.8	1.9

*Numbers in R2030

Table 5. Results of Economic Analysis based on the terms and conditions from Innovation Fund Auction

Results	Scenario 2A	Scenario 2B	Scenario 3A	Scenario 3B	Scenario 4A	Scenario 4B	Scenario 5A	Scenario 5B
NPV (mEUR)*	−48	72	−59	62	−96	25	−7	92

*Numbers in R2030

4. Discussion: Faroe Islands' energy analysis and impacts on Offshore Energy Hubs

This section delves deeper into the implications and interpretations of the findings from section 3. The exploration aims to provide context to the results and extrapolating the relevance to larger regions.

In the preliminary stages of market expansion for green H_2 production, public support can be crucial to catalyze the adoption of this energy source and its derivatives. For this research it is clear, by combining the results from section 3.1 and 3.3, that support mechanisms are needed for developers to be willing to invest in an offshore wind. With the Faroese aim of having green NH_3 driven vessels covering 11% of the maritime sector, it is essential to address the pronounced financial discrepancies between the production expenses and the possible revenue.

Nonetheless, looking at the LCoH calculations for this research, the LCoH estimations are similar to external reports, ranging from 1.7-5.6€/kg [1,2,41,47]. Meaning that the current expectations to H_2 price is not supportive for investments in H_2 setups for developers to get an acceptable income on merchant market conditions. Therefore, supportive instruments can be necessary, given the uncertainties stemming from a lack of a well-established market. Future analysis might include an investigation of building a larger offshore wind farm for long-term needs, if the aim is to transform all vessels to be NH_3 driven. This can potentially result in economy of scale and lower the investment cost and thereby change this analysis. Full adoption of NH_3 for all vessels will not be reachable in this decade. Even the objective of converting 11% of the vessels by 2030 may prove to be a hurdle. Although it might be possible to adapt the energy system for the setup, the availability of the vessels also remains a requisite, which might not be available within the timeframe.

Addressing the economic simulations, the scenarios detailed in section 3.3, illustrate the point at which the developer reaches a break-even NPV. It can be expected that developers are likely to seek a NPV above zero, suggesting that a more aggressive support mechanism is essential to encourage investment in the project. By utilizing the strategy of EHB, it becomes evident that fluctuations in costs and performance can influence decision-making processes, potentially affecting the developer's choice to invest in a Faroese offshore wind farm. On the other hand, according to a report from Wood Mackenzie, offshore wind farms being installed today still carry a comparatively excessive cost compared to other energy sources as onshore wind; however, it is taking the lead in the race to reduce expenses. By 2050, the average Levelised Cost of Electricity (LCoE), and subsequently the average LCoH, are projected to decrease by 68% [1]. This can lead to a potential cost reduction for the investment in an offshore wind farm and H_2 production in the Faroe Islands. Another central pillar in this expected cost-decrease is predicted to come from the cost of electrolyzers, which is assumed to fall 40% in North America and Europe by 2030, according to the Hydrogen Council [48]. With these expected cost reductions, a factor between 1.8 to 3.7 on the H_2 prices calculated in Table 4, might not be needed.

The investigation into the Faroe Islands' energy dynamics in section 3.2, highlights the transition between traditional energy consumption and the potential of offshore wind energy. The 2020 Baseline Scenario depicts a dominant reliance on oil, underscoring the nascent stage of renewable adoption in the region. However, the projection into 2030 presents diverging pathways: the transition in Scenario 1 indicates the current policies of system development [4], contrasted the transformative potential observed in Scenario 2 to 5.

Scenario 2 and 3, introduce an approach by harnessing offshore wind energy exclusively for H_2 production. As mentioned earlier, the configuration in Scenario 2 leads to a smaller offshore wind farm compared to Scenario 3 for the same system setup. Thus, a lower yearly system cost. However, with the small delta in the system cost between Scenario 2 and 3, it is not possible to determine an optimal cost-efficient system setup. Scenario 4 and 5, can ensure utilization of either H_2 or electricity demand with the available wind resource. Though these scenarios have their own set of challenges as the simultaneous production of electricity and H_2 demands. This complicate energy management, particularly during periods of variable wind outputs. In this analysis, H_2 storage is considered to partially overcome this challenge. As the Faroe Islands is a closed energy system, there is a need for a minimum supply of H_2, resulting in curtailment power during high wind periods, even with storage. As storage technology and energy management continues to improve, it might in the future be possible to decrease this curtailment.

EnergyPLAN derived data suggests that in configurations where offshore wind is not dedicated exclusively to H_2 production, the consolidation of all renewable energy sources fails to ensure 100% green H_2 production due to the energy mix of the Faroe Islands. Based on the current dataset, conventional energy sources are necessary for H_2 production in approximately 5% of the annual hourly production without adjusting H_2 storage. When everything else is kept equal and adjusting a single variable, either offshore or onshore wind capacity can remedy this shortfall, however, with consequences. Specifically, to achieve 100% green H_2 production, offshore wind capacity must be a fourfold increase, resulting in a 16.5% cost escalation. Alternatively, onshore wind capacity can be boosted by a factor of 1.8 to cover 100% green NH_3 production, leading to approximately 3% increase in cost. Additionally, both scenarios come with the caveat of heightened energy oversupply during peak wind periods. Consequently, during these specified durations, wind farm owners may have to accept more wind farm curtailment, which can adversely affect the revenue streams. Such dynamics can potentially increase the need for support mechanisms to counter-balance the increased capital investment and the associated disproportional revenue. Alternative, an increase in H_2 storage might be possible to ensure 100% green NH_3 supply, however, this will also include an increase in the system cost, which might make Scenario 4 and 5 more expensive than Scenario 2 and 3.

From an analytical standpoint, Scenario 1 to 5 reinforce the multifaceted nature of energy transitions. It becomes evident that while offshore wind energy presents opportunities, its effective integration requires strategic planning to also ensure that developers will invest in the projects. Therefore, such a transition requires both infrastructural adaptations and strategic policy frameworks that support and incentivize sustainable practices. This study exploration of the Faroe Islands' investment into offshore wind suggests that although offshore wind is a promising path, its full potential depends on the holistic integration of technology, infrastructure, and policy [49–52].

Comparing the results with other research on island-based renewable energy projects reveal similarities in goals of reducing CO_2 emission but differs in specific aims, as the purpose of this study is to examine the feasibility of incorporating offshore wind energy for H_2 production for ammonia driven vessels. For example, a study by Ferreira et. al investigates an integration of renewable energy sources for electricity production at Cape Verde [17], however, the research is not looking into e-fuels. A study of The Orkney Isles, despite having numerous wind turbines and offshore energy testing facilities, face issues with fuel poverty and energy curtailment [49], which is not the case for the Faroe Islands. Sagel et. al address the periodic fluctuations inherent in wind energy by exploring the utilization of ammonia for energy storage purposes. The focus of the study is on leveraging NH_3 as an energy carrier to mitigate energy costs and decrease the CO_2 footprint in Curaçao [26]. This is a similar aim as for this study case for the Faroe Islands, however, the focus of this article is only on utilizing the NH_3 production for the maritime industry. An implementation of a larger offshore wind farm at the Faroe Islands, where the wind production can be used for more applications might change the results. On the other hand, a study of Madeira, which is an isolated energy system, is investigating their ability to handle and manage the energy system and grid stability [50]. Madeira possesses significant solar potential and even though solar is limited at the Faroe Islands, the conditions of being in an isolated area, operating as a self-contained energy system is comparable.

Above are examples of other studies investigating renewable energies system integration at islands, however, while the Faroe Islands' model provides a promising framework for sustainable energy transition, its direct application to other islands must be considered cautiously. Several limitations and contextual factors can affect the feasibility and effectiveness of replicating this model. This could be geographic configuration, which can influence the feasibility of establishing offshore infrastructure. Furthermore, initial investment and technological readiness for an energy transition vary across different regions. Islands closer to shore and linked to other countries may find it less challenging to adopt the Faroe Islands' model, as well as the financial feasibility might be higher, potentially even without support mechanisms.

The following sub-sections will elaborate if learnings from the analysis can be used to assess large-scale Offshore Energy Hubs.

4.1 The Faroe Islands - a unique case for energy assessment

One of the key insights from the Faroe Islands energy assessment was the role of H_2 in transitioning to a larger renewable energy share. H_2 production is often seen essential for modern renewable energy systems, given its capability to store and transport energy [3,37,51–54]. However, the model deployed in this study case of the

Faroe Islands' energy system might be most suitable for hub developments at the shore, especially, if a 100% green H_2 is not needed. As seen in the economic evaluation, this generates the lowest factor added on the H_2 prices, as well as the lowest yearly system cost. Furthermore, future potential synergies with this setup e.g., with district heating (waste heat from H_2 production), biogas production and grass protein production are uninvestigated scenarios [55]. Thus, this might make the system more efficient and reduce critical excess electricity production. Further research is required of the essential technologies to conclude if the shoreline scenario with the potential synergies is even more beneficial for the system integration in the Faroe Islands.

4.2 From microcosm to large-scale: scale effects are not present in the Faroe Islands energy investigation

Compared to the North Sea's potential of minimum 10 Gigawatt as an Offshore Energy Hub [3,51,54,56], the Faroese wind farm size and investment is notably small. This means that the absence of a scale effect in the Faroe Islands energy dynamics are not strictly proportional to size. This has three implications:

1. The data collected for this study case is unaffected by economies of scale, which may lower cost or alter performance metrics in larger systems.
2. Extrapolating from the Faroese's model to larger regions requires careful consideration and cannot be done linearly. Specifically, as a large-scale Offshore Energy Hub entails the potential for cross-border energy trading.
3. The Faroe Islands has a small population and energy demand. Hence, systems which potentially work inefficiently at a smaller scale may result in high efficiencies at larger scale.

Therefore, direct adoption might not be plausible, but the knowledge gained from the Faroe Islands can support the infrastructural and operational strategies fundamentals for integrating Offshore Energy Hubs with H_2 production.

4.3 Economics and the path forward

The journey towards market viability without support mechanisms is usually challenging for new energy technologies and systems. As indicated above, steep learning rates are crucial when upscaling to Offshore Energy Hubs. The larger the Offshore Energy Hubs, the more pronounced these learning curves can be. This means rapid technological advancements, cost reductions, and efficiency improvements are needed.

As initial cost for innovative technology might be high, historical trends in offshore wind LCoE suggest that excessive cost is not indicative of long-term economic viability. With innovation, economies of scale, and lessons from pilot projects like the Faroe Islands, the cost of a H_2 setup can potentially follow a similar downward trajectory. According to Wood Mackenzie, LCoE is globally on a level between 100-120 €/MWh today but expected to decrease to approximately 40 €/MWh by 2050 [1]. Complementarily, a 2020 publication from the International Renewable Energy Agency documented a decline in LCoE from 149 €/MWh in 2010 to 106 €/MWh in 2019, projecting a further decline to 46 €/MWh by the latter half of the 2020s [5]. However, given the current situation with raw material price increase and higher interest rates, it can also be questioned, if the predicted LCoE for offshore wind will decrease according to above mentioned forecast [57,58]. Future evaluations might therefore yield numbers that differ from those detailed in this study.

4.4 Navigating the lessons and challenges from the Faroe Islands to Offshore Energy Hubs

The Faroe Islands, despite its unique characteristics, offers a hint of future of Offshore Energy Hubs. While directly transferring the Faroese approach to large-scale Offshore Energy Hubs can pose challenges, it establishes a baseline that carries essential learnings. Firstly, the importance of adaptive strategies becomes clear. Larger regions will need to tailor their energy based on the specificities of the demand, geography, infrastructure, and socio-economic context. Just as the Faroe Islands must navigate its energy needs without interconnections, larger areas may encounter their own unique set of challenges that demand innovative solutions. E.g., grid code uniformization for cross border trading.

Further considerations can include stakeholder management. With a smaller community and straightforward stakeholder dynamics, the Faroe Islands might not face the same challenges as larger regions, where multiple stakeholders with competing interests can complicate energy projects. A potential gain from investing in offshore wind and H_2 production in the Faroe Islands, as well as for large-scale Offshore Energy Hubs, are social aspects like job creation and reduced dependency on fossil fuels.

5. Conclusion

This study delineated the implication of implementing renewable energy initiatives in the Faroe Islands' energy system, emphasizing offshore wind farms for H_2 production. Thus, addressing the first research question, regulatory uncertainties influence the decision-making process for investing in offshore wind projects in such a way that the merchant risks of a non-carbon regulated market are too high to finance a project achieving the needed scale. For the Faroese ambition of transitioning to renewable energy, establishing an offshore wind farm for power-to-NH_3 conversion in the maritime sector is feasible in a system perspective. However, based on this study's findings, it is advised to introduce a supportive mechanism, like the EHB setup as a progressive step towards accomplishing this ambition.

In response to the second research question, integrating offshore renewable energy into the Faroe Islands' energy system will notably reduce CO_2-related cost, as seen in section 3.2. As mentioned earlier, a potential lowered system cost due to expected cost reduction via technology maturity, may create an economic justification for investment in offshore wind projects. In essence, the feasibility of offshore energy in the Faroe Islands is depending on a mix of regulatory clarity, infrastructural developments, supportive mechanisms, and strategic policy frameworks.

Referring to the last research question, seeing the Faroe Islands as a prototype setup, the evaluation methodologies can be used to assess large-scale Offshore Energy Hubs. As the global momentum shifts towards sustainable energy hubs, this Faroese study, with its challenges and potential gain, can remain as reference point for future setups. Therefore, while the Faroe Islands provide valuable learnings, it is vital to recognize its unique characteristics. Larger regions can use the insights as a foundation, but always critically assess the applicability and modify it to fit the local context. Thus, this study can serve as a beacon for regions navigating similar energy challenges, emphasizing the need for detailed planning and adaptive strategies.

5.1 Future studies: Exploring new horizons of NH3-fueled vessels and green H2 alternatives

In this analysis, it has been assumed that the NH_3 driven vessels can fulfill the same needs and supply as the fuel driven vessels. However, future investigations into the availability and sizes of NH_3 driven vessels compared to fuel driven vessels, as well as the difference in distances travelled per vessel annually and availability of harbor electricity are needed, as these might change the cost perspective. Furthermore, other H_2 based fuels can be considered for the Faroe Islands, as e-methanol. This is not part of this study; however, it can be part of future research.

Another opportunity for future research for the Faroe Islands is to explore other H_2 options. Geographical areas like Iceland, Svalbard, Shetland, and Greenland are contemplating establishing green H_2 production hubs [59–62]. These hubs aim not only to fulfill the individual needs, but also export green NH_3 resulting from the H_2 production. The Faroe Islands can potentially import NH_3 from these hubs, eliminating the investments in offshore wind farms and H_2 production facilities. While assessing the financial viability of this approach is a task for future studies, an immediate advantage foreseen is the reduced yearly system cost. However, it is also worth noting that this approach will not generate local employment opportunities. All of this comes with the assumption that the business cases for the areas are feasible and larger than the one investigated in this assessment to ensure economy of scale.

Furthermore, investigating alternative mechanisms, segmented into various categories as shown in Figure 3, can be considered as a component of future research as it is not part of this paper. Other structure of support mechanisms might give a different result.

When looking at the results in Table 3, which includes the investment cost and the OPEX cost, however, do not including lifecycle sustainability cost, e.g., the cost or benefits to the society for building an offshore wind farm and a NH_3 plant. This can be an area for future research.

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