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Techno-Economic Analysis Incorporating Intelligent Operation and Maintenance Management: A Case Study of An Integrated Offshore Wind and Hydrogen Energy System

Honglin Li[1,2], Mingxin Li[3], James Carroll[3] and Jie Zhang[1,2,4]

[1]Center for Wind Energy, The University of Texas at Dallas, Richardson, TX 75080, USA

[2]Department of Mechanical Engineering, The University of Texas at Dallas, Richardson, TX 75080, USA

[3]Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow G1 1XW, UK

[4]Department of Electrical and Computer Engineering, The University of Texas at Dallas, Richardson, TX 75080, USA

E-mail: `jiezhang@utdallas.edu`

Abstract. In this study, a comprehensive examination of wind-hydrogen energy systems is conducted through detailed techno-economic analysis and sensitivity analysis. The primary emphasis is on optimizing operation and maintenance (O&M) strategies and understanding the impacts of market dynamics. Utilizing Monte Carlo simulations, we first identify the optimal intelligent O&M plan, leading to significant reductions in annual O&M costs ($39.9/MW) and downtime (6.59 days per turbine) compared to conventional methods. The incorporation of prognostics and health management (PHM) further demonstrate a notable impact, leading to a 9.9% reduction in O&M costs and a 10.7% decrease in downtime. In the broader context, these outcomes translate into reductions in the O&M expenditures, total lifecycle costs of the system, Levelized Cost of Hydrogen (LCOH) and Levelized Cost of Energy (LCOE) by 3.9%, 0.75%, 2.4%, and 1.8%, respectively, highlighting the economic benefits of intelligent O&M strategies. The extensive sensitivity analysis, encompassing 54 scenarios, delves into the effects of maintenance strategies, hydrogen prices, wind energy share, and subsidies, revealing nuanced insights into cost savings and operational efficiencies. Notably, intelligent maintenance and favorable hydrogen subsidies effectively reduce LCOH, while the interplay between wind energy share and hydrogen pricing influences system profitability and efficiency, underscoring the complex dynamics at play in optimizing renewable energy systems.

1. Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent necessity to mitigate climate change and transition towards sustainable, low-carbon energy sources [1]. Within this dynamic context, offshore wind energy has emerged as a crucial player, showcasing vast potential for renewable energy generation in offshore regions. However, offshore wind energy generation, while abundant and relatively mature, faces challenges pertaining to intermittency and seamless integration into existing energy grids [2]. This variability in wind energy production therefore necessitates the development and integration of robust energy storage solutions to ensure reliability and continuity in power supply, thereby addressing the critical challenge of wind energy variance. Simultaneously, hydrogen is increasingly recognized as a versatile energy carrier and storage solution, seamlessly integrating with renewable energy sources to offer long-term energy stability and pathways for decarbonization across various sectors. Importantly, the future applications of hydrogen are vast, extending to fuel transportation, power industrial processes, and even support residential heating, thereby paving the way towards a fully sustainable energy ecosystem. Consequently, hydrogen presents a practical solution for storing surplus energy during periods of high production and efficiently delivering it to meet high demand or supplement low renewable generation, ensuring a balanced and resilient energy system [3]. Integrating offshore wind and hydrogen technologies (as illustrated in Fig. 1) represents a promising synergy that can couple offshore wind turbines directly with electrolyzers, facilitating the on-site production of hydrogen. We assume that the research in this paper is based on an on-site hydrogen production environment. This arrangement not only optimizes energy utilization but also enhances the overall stability of the energy grid. This innovation technology contributes significantly towards the attainment of ambiti

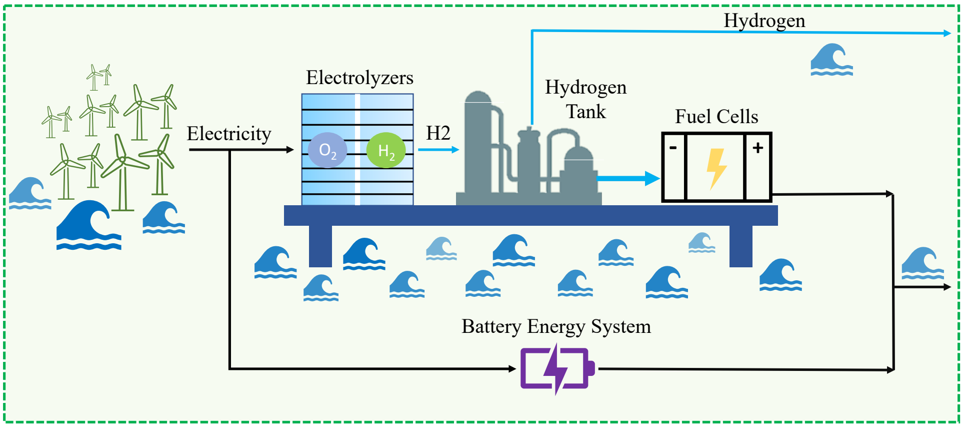

Figure 1. Schematic diagram of an integrated offshore wind and hydrogen system.

There have been a number of studies focusing on techno-economic analysis of hybrid renewable energy systems. For instance, our previous studies [4, 5] have focused on the technical feasibility and economic advantages of operating a hybrid wind and hydrogen system, as well as the advantages of hydrogen in playing the role of energy storage. In the study of the techno-economic analysis of hybrid solar and hydrogen systems [6, 3], the authors also focused on the economic aspects of the system only in the context of meeting the technical requirements of the system. However, existing techno-economic analysis of hybrid renewable energy systems commonly relies on a projected O&M cost value derived from conventional corrective or time-based maintenance as the input. However, this projected value tends to disregard the economic advantages brought by intelligent O&M management practices. The advent of intelligent O&M management, harnessed through cutting-edge technologies like condition monitoring, predictive analytics, and digital twins, signifies a highly promising trajectory within the realm of renewable energy [7]. This inadvertent oversight results in an inability to account for the prospective gains of intelligent O&M within the techno-economic analysis, consequently leading to the formulation of systems that may fall short of anticipated performance benchmarks in the forthcoming digital landscape.

This paper presents a sophisticated techno-economic analysis framework for integrated offshore wind and hydrogen systems, emphasizing the integration of intelligent O&M management. The framework systematically evaluates technical performance and economic feasibility, combining technical insights with economic metrics to assess the sustainability of the

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technology. The novel aspect of this analysis is the incorporation of intelligent O&M strategies, influenced by digital advancements, to predict and mitigate potential failures, thereby reducing maintenance costs. This approach customizes maintenance forecasts to specific operational characteristics of the system, enhancing the accuracy and reliability of the analysis over traditional methods. The result is a more precise and dependable evaluation tool for assessing the economic and technical viability of integrated renewable energy systems.

2. Methodology

The methodology of this study entails a comprehensive modeling approach for the techno-economic analysis of IES. It incorporates a wide array of factors such as O&M management, energy balance, storage, capacity, grid interactions, and demand peaks, aiming to minimize the total cost of the IES by accounting for various cost components and revenue streams. A two-stage optimization model is employed, focusing initially on maintenance optimization based on the remaining useful life of IES subsystems. This first stage utilizes a predictive maintenance strategy optimized by particle swarm optimization to minimize O&M costs, leveraging digital technologies for condition monitoring and predictive analytics. The overall methodology emphasizes a holistic integration of technological, financial, and operational considerations to optimize IES performance.

2.1. First-stage optimization: Operation and maintenance

In this section, a mathematical model is developed to formalize the intelligent O&M for the offshore wind farm, as the first-stage O&M optimization. The model is extended based on [8].

Connectivity, amount of data, new devices, inventory reduction, customization, and controlled production enable Industry 4.0 [9]. In the era of Industry 4.0, the integration of prognostics and health management (PHM) systems holds the potential to effectively anticipate impending failures. This capability offers a promising avenue to mitigate the likelihood of failure events, enhance the operational availability of industrial machines, and curtail the costs linked to maintenance operations. The O&M model in this paper is developed in this context. Leveraging PHM technology, the model facilitates the proactive scheduling of maintenance actions, thereby enabling the anticipation of the remaining useful life (RUL) of wind turbine components.

Assuming that an offshore wind farm consists of $\mathcal{K}$ turbines, each offshore wind farm is a series system composed of $\mathcal{I}$ components. The offshore wind farm is inspected at a regular interval $\mathcal{M}$. The designed lifetime of the wind farm is $\mathcal{L}$. After the inspection, the wind turbine component states are assumed to be observable and the RUL of components can be predicted. Denote a as the number of inspection since the offshore wind farm begins to operate, and a degradation indicator ψ_{ik}^a is used to represent the degradation state of component i ($i = 1, 2, \ldots, \mathcal{I}$) at turbine k ($k = 1, 2, \ldots, \mathcal{K}$) at the a-th inspection.

By using the PHM system, at the a-th inspection, the RUL of component i at turbine k is predicted as s_{ik}^a. The current operational age of the component is r_{ik}^a, and the degradation indicator ψ_{ik}^a is calculated as

$$\psi_{ik}^a = \frac{r_{ik}^a}{\left(r_{ik}^a + s_{ik}^a\right)} \cdot 100\%. \tag{1}$$

Maintenance thresholds ψ_{ik}^+ and ψ_{ik}^- are introduced to determine the degradation state of the components and perform respective maintenance actions. The maintenance actions include:

- **Basic maintenance** ($\psi_{ik}^a < \psi_{ik}^-$): The component is in a good state. In this case, the basic repair including lubricating, adjusting, tightening is conducted on components to maintain the component state.
- **Preventive maintenance** ($\psi_{ik}^- \leq \psi_{ik}^a < \psi_{ik}^+$): The component is degraded, requiring a preventive maintenance to recover the component state with an age reduction u.

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- **Preventive replacement** ($\psi_{ik}^{+}\leq \psi_{ik}^{a}$<100%): The component is in an aged state, and it should be replaced preventatively to avoid failure events.
- **Corrective replacement** (100%$\leq \psi_{ik}^{a}$): The component has failed and requires replacement.

Given the health state of the offshore wind turbine components, the decision-maker will decide whether to initiate a maintenance cycle. Maintenance cycles refer to the sequence of events from the definition to the completion of maintenance tasks. The maintenance cycles are initiated when the following scenarios occur:

- Scenario 1: There are a certain number of failed components, which will cause the wind turbine to shut down, resulting in constant shutdown losses. When the number of the failed components in the offshore wind farm reaches Q, where $Q = \mathcal{K}\mathcal{L}\xi$, maintenance cycles need to be triggered.
- Scenario 2: When the number of the aged components in the offshore wind farm reaches P, where $P = \mathcal{K}\mathcal{L}\eta$, maintenance cycles are determined to be triggered.

The decision vector of the model, $\mathbf{\Omega} = (\psi_{ik}^{+}, \psi_{ik}^{-}, \xi, \eta)$, controls the frequency of maintenance cycles and the range of components qualified for various types of maintenance. After determining to initiate a maintenance cycle, the service vessels and technicians are mobilized to conduct maintenance. The mobilisation time of the maintenance cycle $m_n^{\mathrm{H}} \sim$ Weibull(ε^{M},σ^{M}).

In the total maintenance cycle N over the lifetime of offshore wind farm $\mathcal{L}$, the total O&M cost is C^{R} and the production losses is C^{P}. The optimization objective is to minimize the sum of annual O&M costs and production losses, d_{c}, aiming to improve the economic performance of the offshore wind farm. The objective function is formulated as

$$\min_{\mathbf{\Omega}} \quad d_{\mathrm{c}} = \frac{C^{\mathrm{R}} + C^{\mathrm{P}}}{\mathcal{L}} \tag{2}$$

Under the optimal solution $\mathbf{\Omega}^{*}$, the obtained O&M costs C^{R} and the average annual downtime of each wind turbine D^{w} will be used as input parameters for the next stage of optimization.

The above O&M model represents the intelligent O&M management by leveraging the PHM system. Compared to hydrogen energy assets, the current condition monitoring system and PHM technology is more mature for offshore wind systems. Hence, in this case, it is assumed the intelligent O&M technology is only applicable for offshore wind farms in this model. They Monte Carlo simulation used in this model aims to estimate the expected O&M costs for offshore wind farms under this intelligent O&M context, which does not affect hydrogen systems.

In comparison, we also develop a conventional maintenance strategy representing the baseline, where the maintenance cycles are triggered periodically without considering intelligent O&M management. In this context, the PHM system is not usable, indicating the RUL of components is unpredictable. In maintenance cycles, the failed components are replaced and the degraded components are repaired preventatively. The decision variable is the constant frequency of maintenance cycles, F^{M}.

2.2. Second-stage optimization: System Configuration

Moving to the second stage, the focus shifts to a mixed-integer linear program (MILP) that lays the foundation for the techno-economic analysis. The MILP framework enables concurrent optimization of operational strategies within the IES. The FICO Xpress solver is employed to solve this optimization problem, ultimately yielding the optimal dispatch strategies. These strategies are judiciously selected from a pool of candidates, tailed to meet energy demands at each time interval while concurrently minimizing the lifecycle cost. For an in-depth understanding of the mathematical optimization model employed, please consult our prior study

[5]. In this study, we have enhanced our previous research by examining how the increased wind energy share and hydrogen production subsidies can impact the system. We've looked closely at how more wind energy affects costs, efficiency, and stability, and how subsidies can make hydrogen energy more economically attractive. Our approach provides deeper insights into these factors, offering a more detailed understanding of renewable energy systems and guiding future strategies and decisions in this field. The entire optimization process yields a set of critical outputs, including:

- **Total system expenditure:** The cumulative expenses incurred by the IES encompasses installation costs for all components, O&M expenses, electricity procurement expenses, tax implications, incentives, and profits generated from hydrogen sales.
- **Operational trade-offs:** The optimization procedure also identifies the most favorable equilibrium between wind and hydrogen production operations. This equilibrium ensures the effective utilization of energy resources while maintaining optimal grid interactions.
- **LCOH:** A critical metric for gauging the economic feasibility of hydrogen production within the IES framework.
- **LCOE:** By calculating the LCOE for the entire integrated system, valuable insights are obtained regarding its competitiveness standing compared to alternative energy sources.

3. Numerical Experiments

On October 27, 2023, the U.S. Federal Bureau of Ocean Energy Management (BOEM) announced the finalization of four Wind Energy Areas (WEAs) in the Gulf of Mexico [10]. Figure 2 delineates Area L, encompassing 91,157 acres with a projected installed capacity of 1,107 MW, a maximum water depth of 29 meters, and a minimum distance of 85.2 km to Texas. Significantly, its proximate continental region serves as a crucial petrochemical hub along the Gulf Coast, necessitating approximately 4,900 metric tons of hydrogen daily. This estimate was deduced by extrapolating the capacities of ten refineries in the region and factoring in the proportion of hydrogen utilized in crude oil processing. Consequently, this study posits the hypothetical installation of a hybrid energy system in Area L, targeting a wind farm capacity of 800 MW. The temporal scope for this analysis is set over a 20-year planning horizon. The economic assessment within this study employs the 2022 hourly locational marginal prices for the Houston lo (ERCOT) [11].

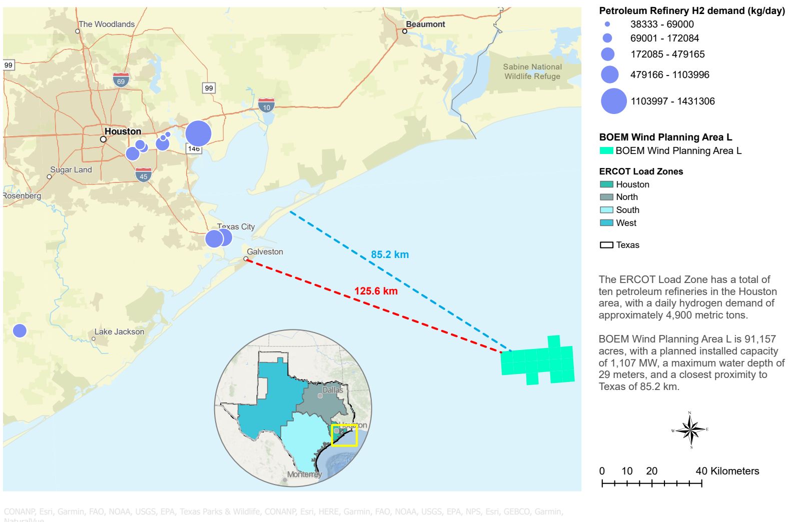

Figure 2. Offshore wind farm location and hydrogen demand.

Figure 3 illustrates the capacity factor for wind energy in the specified region at a hub height of 90 meters. This factor was determined using the System Advisor Model (SAM) [12] for detailed performance simulations, drawing upon meteorological data provided by the WIND Toolkit [13]. This approach ensures a comprehensive analysis of the wind energy potential based on historical and predictive weather patterns at the designated height. Table 1 lists some of the key parameters used in the second-stage optimization.

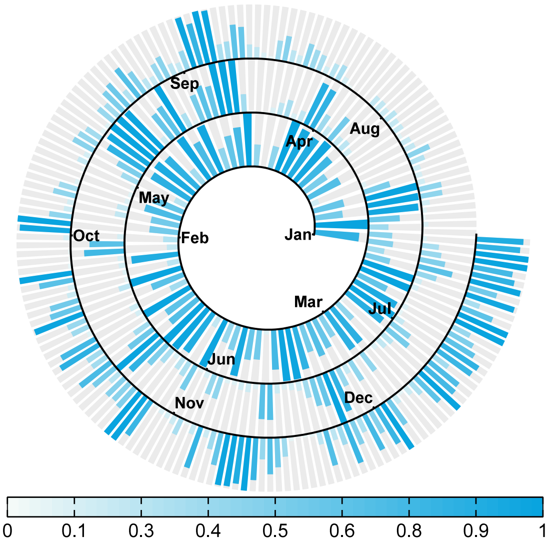

Figure 3. Offshore wind capacity factor.

For the first-stage optimization, parameters relevant to the failure and maintenance of offshore wind turbines are derived from the literature [8, 14, 15] and are listed in Table 2. The scale parameters and shape parameters of the mobilization time is 4 weeks and 3.1, respectively, and the mobilization cost is $88,000 [8]. The service vessel-related parameters are estimated from [8, 16] and shown in Table 3.

Table 1. Key assumptions in the integrated energy system setup [5, 17, 18, 19, 20]

Parameter	Cost
Electricity consumed per kg of hydrogen produced (low thermal energy)	55 kWh/kg
Wind turbine installation cost (Applicable to this study only)	$353 /kW/km
Water slope for electrolyzer	9 kg/kg H_2 production
Electrolyzer installation cost	$36,744 /kg/h
Fixed electrolyzer O&M cost	$1,828 /kg/h
Variable electrolyzer O&M cost	$0.024 /kg
Hydrogen tank installation cost	$525 /kg
Soft water price	$0.01 /kg
Oxygen price	$0.01 /kg

3.1. O&M optimization

The O&M model simulation incorporates various stochastic parameters, resulting in a stochastic output. To estimate the expected value of the objective function and guide the search for optimal solutions, we conduct a Monte Carlo simulation with 1000 repetitions. The optimal solution of the intelligent maintenance strategy is (51.3%, 93.9%, 4%, 0.8%). The annual O&M costs

Table 2. Failure and maintenance parameters for components

Component	Failure distribution		Cost (k$)		Age reduction of major repair	Inspection and RUL prediction interval (days)
	Scale parameter (days)	Shape parameter	Failure replacement	Basic repair		
Rotor blade	3000	3	203.5	4.4	0.4	60
Speed train	3750	2	49.5	1.1		
Gearbox	2400	3	253	5.5		
Generator	3300	2	66	0.6		
Pitch system	1858	3	15	0.6		

Table 3. Service vessel-related parameters

Vessel	Daily cost rate (k$)	Technician		Working shift (hours)
		Number	Daily rate (k$)	
Heavy lift vessel	55	8	0.66	24
Field support vessel	19.8	4		12
Crew transfer vessel	8.8	2		12

are \$39.9/MW and the annual downtime per wind turbine is 6.59 days. Annual O&M costs, as well as wind turbine downtime, are heavily influenced by factors such as wind farm size, site conditions, and distance to the shore. Therefore, these results are tailored specifically to its defined parameters and may not directly extend to other contexts or conditions. In comparison, the optimal maintenance frequency of the conventional maintenance strategy is 1.17 years. The annual O&M costs are \$44.3/MW and the annual downtime per wind turbine is 7.85 days. The incorporation of PHM systems can reduce 9.9% O&M costs and 10.7% downtime.

3.2. Techno-economic analysis of integrated energy systems
The first-stage optimal results are integrated into the second-stage optimization to evaluate the impacts of conventional and intelligent O&M strategies on the overall system performance. As depicted in Fig. 4, the variations in O&M expenditures, total lifecycle costs, the LCOH and the LCOE of the hybrid system are analyzed, both before and after the implementation of the O&M strategies. The analysis indicates a respective reduction of 3.9%, 0.75%, 2.4%, and 1.8% in these parameters, illustrating the efficacy of the optimized O&M strategies in enhancing the economic viability of the wind energy system. For the LCOE and LCOH, although there has not been a lot of absolute numerical reduction, there's been a very substantial gain in terms of the entire life cycle of the hybrid system, as shown by the total cost.

4. Sensitivity Analysis
The study has conducted a detailed sensitivity analysis of 54 scenarios across four key categories to understand the varying impacts on wind-hydrogen integrated energy systems. Maintenance strategies were analyzed by comparing conventional schedule-based maintenance (costing \$44.4/kW) with intelligent, predictive maintenance (costing \$40.7/kW), highlighting potential cost savings. The analysis also examined the effects of fluctuating hydrogen prices (\$2/kg, \$4/kg, \$6/kg) on system profitability and break-even points. The study further investigated the potential percentage of wind power generation into hydrogen production (30%, 60%, 90%), assessing its implications for system performance, grid stability, and energy storage. Additionally, the impact of hydrogen system subsidies (ranging from \$0.75/kg to \$3/kg) [21] was evaluated, illustrating how policy and economic incentives can significantly influence the adoption and success of renewable energy technologies. A baseline scenario with intelligent O&M, 100% wind energy, hydrogen priced at \$4/kg, and a subsidy of \$3/kg was established. The comprehensive sensitivity analysis provides a nuanced view of the system's responsiveness to

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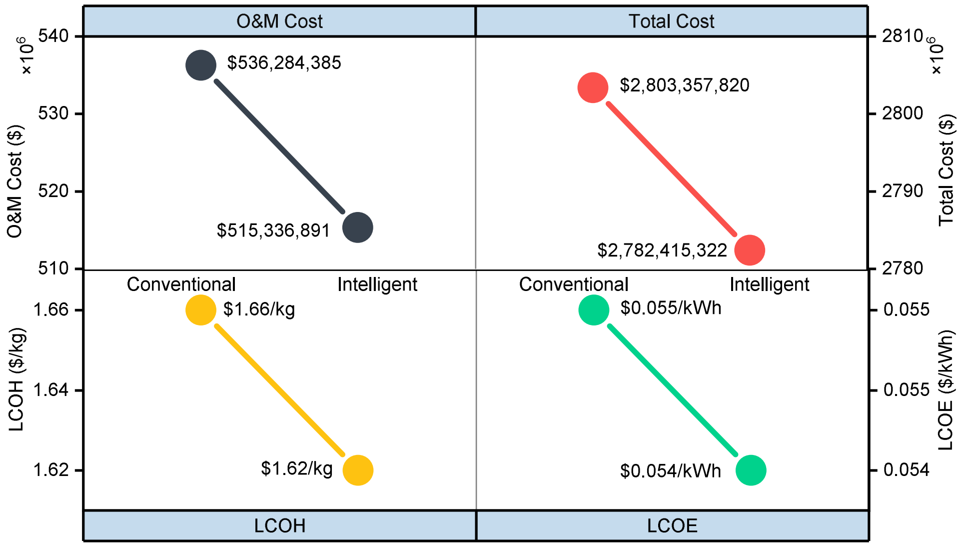

Figure 4. Differences in O&M cost, total cost, LCOH and LCOE over the system lifecycle for intelligent and conventional maintenance strategies.

various factors, guiding strategic decisions and policy formulations for optimizing wind-hydrogen integrated energy systems.

Figure 5 elucidates the dynamic interplay between electrolyzer capacity and utilization across varying levels of wind energy share and hydrogen selling prices. The graphical representation reveals a clear trend: as wind energy share intensifies, the system tends toward installing larger electrolyzers to capitalize on the increased availability of wind power. Correspondingly, the electrolyzer capacity exhibits a gradual augmentation with the escalation of hydrogen selling prices, indicating an inclination to invest in larger capacity for higher revenue potential. Interestingly, while the capacity expands, the optimal utilization of the electrolyzer peaks at a 60% wind energy share. Beyond this point, notably at high wind shares like 90%, the allure of higher profits at elevated hydrogen prices prompts the system to opt for even larger electrolyzers. However, this expansion in capacity paradoxically leads to a decrease in utilization rates. This phenomenon suggests a strategic balancing act, where the system installs capacity sufficient to maximize profits from high selling prices, yet the actual utilization is moderated by the variable nature of wind energy supply and the demand dynamics of hydrogen, illustrating the complex decision-making matrix in optimizing renewable energy systems.

Figure 6 demonstrates how changes in hydrogen selling price and wind energy share affect the profitability of hydrogen, electricity, and oxygen in an energy system. The diagram employs a logarithmic scale ($\ln x$) on the horizontal axis to better detail shifts, especially for the smaller oxygen segment. It shows that as the hydrogen selling price increases, hydrogen's share of profitability significantly rises. In contrast, higher wind energy share boosts the profitability of electricity and oxygen, but reduces that of hydrogen. This is aligned with previous findings suggesting that increased wind share leads to the use of smaller electrolyzers, thus a greater portion of electricity is used for the grid, decreasing the relative profitability of hydrogen. This complex interaction emphasizes the need for strategic management of resource allocation, understanding market forces, and leveraging technology to optimize the economic performance of integrated renewable energy systems.

In our final step analysis, we investigated the impact of four combined dimensions on the LCOH as depicted in Fig. 7. It is observed that a reduction in wind O&M costs and an increase in hydrogen subsidies contribute to a decrease in LCOH, underscoring the positive effects of operational efficiency and supportive economic measures. The connection between wind energy

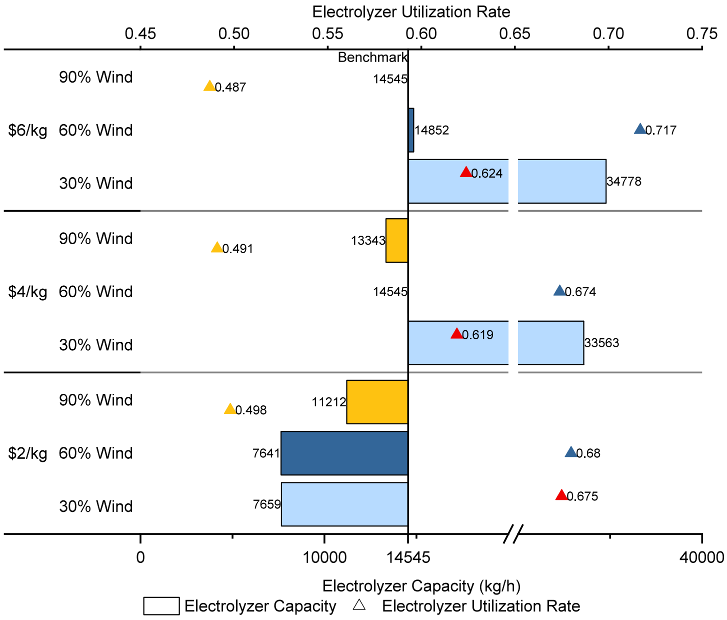

Figure 5. Variation of electrolyzer capacity and utilization rate for different hydrogen selling prices and different wind energy share scenarios. The bars correspond to the bottom horizontal axis, indicating electrolyzer capacity across various scenarios, while the solid triangles align with the top horizontal axis, denoting electrolyzer utilization rates for respective scenarios. The different colors in the figure represent different wind ratios in hydrogen production.

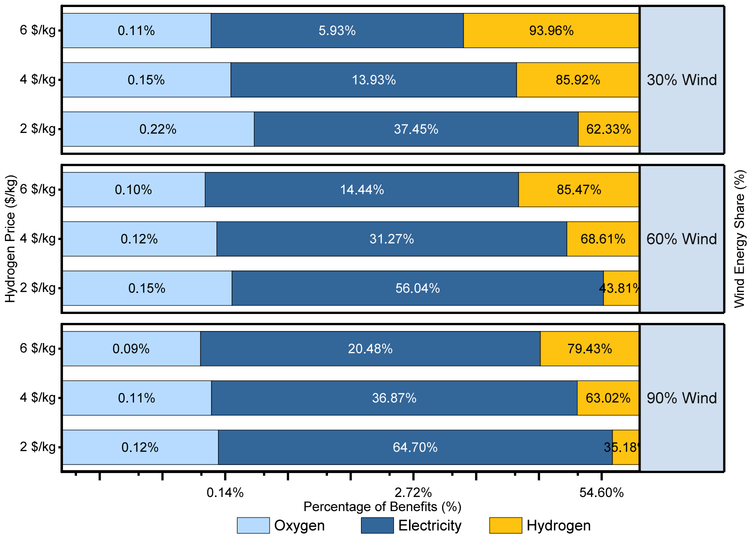

Figure 6. Profitability ratios for hydrogen, oxygen, and electricity across varied wind energy share and hydrogen price scenarios over system lifecycle. The diagram utilizes a logarithmic scale ($\ln x$) on the horizontal axis for enhanced granularity.

share ratio and LCOH in wind-hydrogen systems is detailed and multifaceted. Increasing wind energy share typically leads to a higher LCOH, as the system shifts from low-cost or even zero-cost grid electricity to more wind power, which incurs certain costs despite its low marginal price. Conversely, hydrogen pricing's effect on LCOH is dependent on wind energy share levels. For lower shares (30% and 60%), a rise in hydrogen price tends to decrease LCOH by promoting the use of more economical electricity, enhancing overall system efficiency and cost. However, at higher share levels, specifically 90%, the situation is reversed; increased hydrogen prices cause an increase in LCOH due to the need for larger systems and reduced efficiency from not always being able to use low-priced grid electricity. This delicate balance between wind energy share and hydrogen prices indicates the importance of carefully managing these factors to maintain cost-effective hydrogen production in predominantly wind-powered systems.

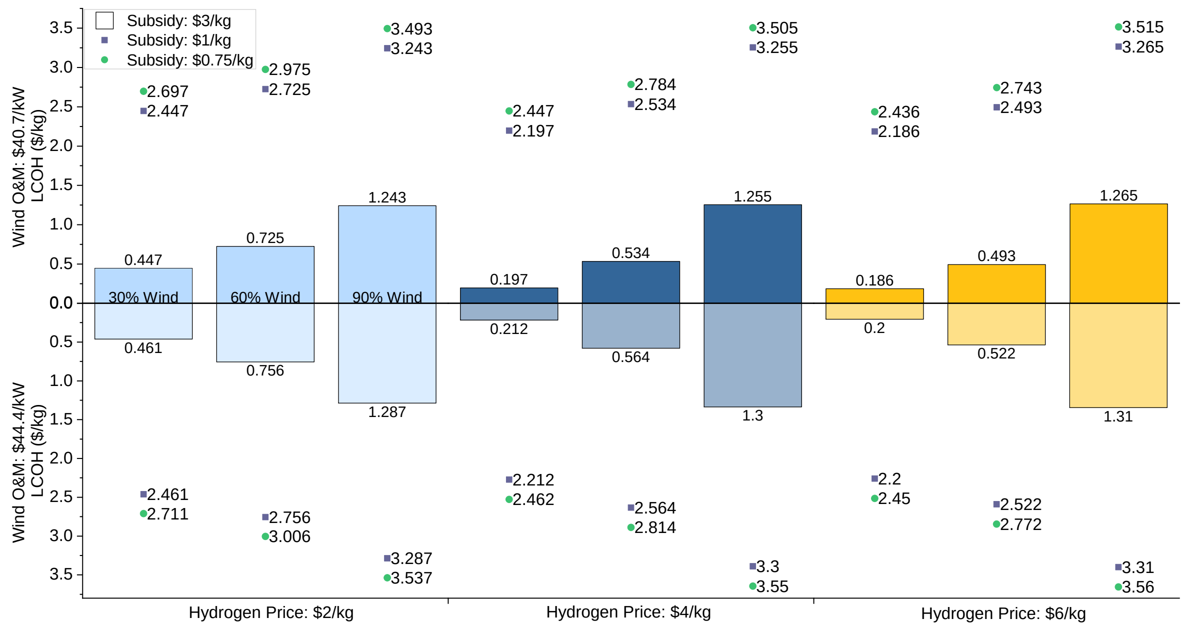

Figure 7. LCOH for various scenarios. The upper portion depicts the effects of intelligent O&M expenditures on LCOH, while the lower part shows the impact of conventional O&M costs. Horizontally, it delineates three hydrogen price categories, within which the effect of varying wind energy shares in hydrogen production on LCOH is expressed through bar charts. Additionally, within each wind energy share subcategory, the diagram indicates the influence of different hydrogen subsidy on LCOH, denoted by solid squares and circles.

5. Conclusion

The economic viability and performance of wind-hydrogen integrated energy systems are heavily influenced by operational strategies, market conditions, and policy incentives. Key findings of this study include the benefits of reducing wind O&M costs and increasing hydrogen subsidies to lower the LCOH. However, the impact of wind energy share and hydrogen pricing on LCOH is complex. While higher wind energy shares generally increase LCOH due to reliance on more expensive electricity, variations in hydrogen prices can either decrease or increase LCOH depending on the wind energy share level and system efficiency. These results highlight the need for balanced operational, economic, and technological strategies in renewable energy system optimization. The study emphasizes the importance of nuanced strategic planning and policy formulation in the evolving renewable market, providing valuable insights for future renewable energy investments and policy development. The future directions for expanding this research are diverse and promising. We aim to explore the application of PHM technology to both wind energy and hydrogen systems, enhancing their operation and maintenance through intelligent solutions. Additionally, we plan to delve into the effects of wind farm maintenance on hydrogen production, seeking ways to optimize the efficiency and synergy between these renewable energy systems.

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