

Article

Optimal Investment Strategy for Off-Grid Offshore Wind Hydrogen Production: Hybrid and Standalone PEM Electrolyzer Configuration Comparison

Hanyi Lin ^{1,2,†}, Qing Tong ^{3,*,†}, Sheng Zhou ³  and Cuiping Liao ^{1,2,*}

¹ School of Energy Science and Engineering, University of Science and Technology of China, Hefei 230026, China; linhanyi@mail.ustc.edu.cn

² Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China

³ Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China; zhshinet@tsinghua.edu.cn

* Correspondence: tongqing@tsinghua.org.cn (Q.T.); liaocp@ms.giec.ac.cn (C.L.)

† These authors contributed equally to this work.

Highlights

What are the main findings?

- The hybrid ALK–PEM electrolyzer configuration, through coordinated operation, reduces the levelized hydrogen cost by approximately 15% versus standalone PEM, where low-cost ALK handles stable base-load power and fast-responsive PEM serves as a peak-shaving regulator under fluctuating offshore wind.
- Real-options analysis reveals substantial hidden investment value overlooked by conventional NPV, advancing optimal investment timing by up to five years and increasing project value by up to 17 times for the hybrid configuration, particularly under slow technological progress scenarios.

What are the implications of the main findings?

- Targeted policy support for hybrid ALK–PEM demonstration projects, combined with stable green hydrogen pricing mechanisms, can effectively lower cost barriers and accelerate far-offshore wind-to-hydrogen commercialization.
- Integrating real-options frameworks with dynamic operational modeling provides timing-sensitive investment decision-support superior to conventional DCF analysis, enabling investors and policymakers to capture deferral flexibility and optimize entry timing for long-horizon renewable hydrogen projects.

Abstract

Developing far-offshore wind power integrated with hydrogen production represents a critical pathway for China's energy decarbonization. However, the investment prospects of off-grid offshore wind-to-hydrogen projects remain highly uncertain due to volatile technology costs and hydrogen prices, complicating the evaluation of project value and optimal timing. To address the oversimplified treatment of electrolyzer operation and the limited consideration of alkaline electrolyzers in the existing studies, this paper proposes an integrated assessment framework that combines time-series operational simulation with real options analysis. A detailed dynamic model of an alkaline (ALK)–proton exchange membrane (PEM) hybrid configuration is developed to simulate the coordinated hydrogen production under fluctuating wind power. Technical learning effects and stochastic hydrogen price processes are incorporated, and the least-squares Monte Carlo method is applied



Academic Editor: Damien Guilbert

Received: 27 January 2026

Revised: 14 March 2026

Accepted: 20 March 2026

Published: 24 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

to determine the optimal investment strategies. A case study of a planned far-offshore wind farm in Guangdong indicates that, compared with a standalone PEM configuration, the hybrid configuration reduces the levelized hydrogen cost by about 15%, increases the investment value by up to 17 times under slow technological progress, and brings forward the optimal investment year by five years, from 2039 to 2034. Sensitivity analysis shows that expected hydrogen prices and discount rates dominate the investment outcomes.

Keywords: offshore wind energy; ALK–PEM electrolyzer; dynamic operation model; real options model; optimal investment decision

1. Introduction

With the maturity of wind power technology and the increasing need for energy decarbonization, far-offshore wind development has attracted growing attention in China's coastal provinces. By 2023, China's cumulative grid-connected offshore wind capacity reached 36.5 GW [1], making it the largest offshore wind market in the world. The majority of these projects are located in nearshore areas. Studies indicate that far-offshore resources account for over 67% of China's total offshore wind energy potential [2], and far-offshore wind offers higher wind utilization rates and capacity factors compared to nearshore sites. Developing far-offshore wind resources located more than 80 km from the coast therefore represents an inevitable and strategically important future trend [3]. Despite high expectations for its development, the increase in distance from the shore leads to excessive power transmission costs, significantly raising the investment costs. This is primarily due to the high expense of long-distance transmission infrastructure, particularly high voltage direct current cables [4], thereby slowing far-offshore wind deployment. With advancements in electrolytic hydrogen production technologies, the emerging mode of using off-grid offshore wind to produce hydrogen has gained attention as a promising alternative [5]. Research shows that, at sufficient offshore distances, producing hydrogen from offshore wind for transportation is more cost-effective than direct electricity transmission [6,7]. In the future, as the feed-in tariff declines, selecting high-capacity-factor offshore wind for hydrogen production will yield economic returns that are comparable to conventional power projects [8].

In existing techno-economic studies of wind-to-hydrogen systems, both discounted cash flow (DCF) and real options (RO) methods are widely applied. In DCF-based analyses, metrics such as the net present value (NPV) [9,10] and levelized cost of hydrogen (LCOH) [11–14] are commonly used to evaluate the economic performance of wind-to-hydrogen projects. Quang et al. [15] optimized the ratio between the electrolyzer capacity and offshore wind capacity, finding that an appropriate electrolyzer size can substantially reduce hydrogen production costs. However, in uncertain environments, decision flexibility carries a significant implicit value. For offshore wind-to-hydrogen projects, which are highly uncertain and have long payback periods, DCF often underestimates the future investment value. Real options (RO) analysis is an increasingly popular method for assessing the value of projects, particularly under uncertain conditions, since it allows for flexible decision making. Flora et al. [16] applied RO to assess the investment value of PEM electrolyzers for wind-to-hydrogen projects, finding that a higher feed-in tariff led to a greater option value of waiting to invest. Paul et al. [17] investigated the future investment value for renewable-hydrogen systems coupled with the grid, concluding that the current electricity and natural gas prices in Germany limit hydrogen development and delay optimal investment timing. Liu et al. [18] integrated lifecycle optimization into an

RO model to forecast the cost reduction potential and investment value for both the ALK and PEM electrolyzer configurations. Overall, RO analysis provides a feasible approach for investment decision-making in wind-to-hydrogen projects.

However, a review of the existing studies reveals two main limitations in the current investment decision research on wind-to-hydrogen projects. First, many studies oversimplify electrolyzer modeling in technical analyses, neglecting specific operational strategies. For example, electrolyzers are often idealized as single units, and their capacity is calculated using a fixed hydrogen production coefficient [8,19,20]. In practice, large-scale hydrogen projects typically consist of multiple smaller electrolyzer units operating in combination. Moreover, some studies consider time-series power allocation using algorithms but ignore the fact that the power at each moment is dynamically linked to the preceding time step. This dynamic correlation is influenced by factors such as the number of electrolyzer units, load range, and ramp rates. Incorporating detailed electrolyzer operation strategies into technical analysis is therefore essential for generating results that accurately reflect real-world performance.

Second, due to the high variability of renewable energy sources like wind power, PEM electrolyzers are the primary focus of most off-grid renewable hydrogen studies, while alkaline (ALK) electrolyzers are often neglected because of their smaller load range and longer start-up/shutdown times. In practice, however, technological advancements and appropriate operational strategies make it feasible to implement a hybrid ALK–PEM electrolyzer configuration, in which the ALK units handle the more stable portion of power and PEM units accommodate highly fluctuating power. Table 1 presents a comparison between standalone PEM and hybrid electrolyzer configurations. The use of low-cost ALK electrolyzers in combination with optimized operational strategies represents a demonstration experience for renewable-hydrogen deployment in China and warrants further study [21,22]. Additionally, within their operating range, the electrolyzer efficiency varies with power input—a dynamic characteristic that has been largely overlooked in previous research. Furthermore, ongoing advances in electrode materials, such as platinum nanoparticles supported on nickel-molybdenum-oxide for the hydrogen evolution reaction (HER), continue to drive improvements in electrolyzer efficiency [23], suggesting that static efficiency assumptions will become increasingly inadequate.

Table 1. Comparison of two off-grid hydrogen production configurations.

Title 1	Single Electrolyzer Configuration	Hybrid Electrolyzer Configuration
Key Components	PEM + Energy Storage	ALK + PEM + Energy Storage
Function	PEM: H ₂ production; Energy Storage System (ESS): Smooths wind power	ALK: Stable power; PEM: Volatile power; ESS: Ensures safe operation
Technology Maturity	Relatively high	In Development
Advantages	Simple and Reliable	Lower Overall Cost
Disadvantages	Higher CapEx (Oversized equipment)	Highly Demanding Control

As summarized in Table 2, a comparison of the present study with the recent literature further highlights these gaps. While several studies have applied real options analysis to wind-to-hydrogen investment decisions [16,17], they rely on simplified electrolyzer models that either treat the electrolyzer as a single unit with a fixed production coefficient or neglect the dynamic coupling between successive time steps. Conversely, more detailed operational studies [17,24,25] have not extended their analyses to investment optimization,

and none has considered a hybrid ALK–PEM configuration in conjunction with a real options framework. The present study addresses both gaps simultaneously.

Table 2. Comparison of the present study.

Study	Analysis Method	Electrolyzer Type	Dynamic Operation Model	Hybrid ALK–PEM	Investment Optimization
Quang et al. [15]	DCF	PEM	No	No	No
Flora et al. [16]	Real Options	PEM	No	No	Yes
Paul et al. [17]	Real Options	PEM	No	No	Yes
Giampieri et al. [24]	DCF	PEM	No	No	No
Bødal et al. [25]	DCF	PEM	Partial	No	No
Fabianek et al. [17]	Real Options	PEM	No	No	Yes
This study	Real Options	ALK–PEM hybrid	Yes	Yes	Yes

The future of off-grid offshore wind-to-hydrogen investment remains uncertain. On the one hand, technological uncertainty arises from potential advances and alternative solutions; on the other hand, market uncertainty stems from future green hydrogen price fluctuations and the potential introduction of carbon markets. In response to these challenges, this study aims to address the following questions: (1) How should investors assess the investment value of offshore wind-to-hydrogen projects and determine the optimal timing for investment? (2) Compared with standalone PEM hydrogen production projects, how does incorporating ALK units into a hybrid electrolyzer configuration affect the project value and investment timing?

To optimize the investment strategies for off-grid offshore wind-to-hydrogen projects, this study proposes a framework that integrates realistic electrolyzer operational strategies with real options simulation to evaluate investment time and value. Compared with existing techno-economic analyses of electrolytic hydrogen systems, the contributions of this study are as follows:

- (1) Incorporation of realistic multi-electrolyzer operational strategies into the modeling framework. Considering that large-scale hydrogen projects are composed of multiple smaller electrolyzer units and that the stable operation of ALK electrolyzers is subject to various constraints, this study models the operation of multiple electrolyzers by incorporating dynamic hydrogen production efficiency, power range limits, ramp-rate constraints, and cold-start restrictions. This allows for the simulation of actual hydrogen output under fluctuating wind conditions, producing results that more accurately reflect real-world performance.
- (2) Development of a real options model. A real options framework is established to evaluate investment decisions, incorporating projected technology investment costs through learning curves, while simultaneously accounting for multiple market uncertainties, including hydrogen prices and carbon trading. The model captures the option value of deferring investment—an aspect often overlooked in traditional analyses—enabling the identification of the optimal investment timing for hydrogen projects.
- (3) Comparison of standalone PEM and hybrid electrolyzer configurations. The study analyzes how integrating ALK units influences the investment value and timing, providing quantitative guidance for potential investors and policymakers in decision-making.

2. Methods and Model

The overall research framework is shown in Figure 1. First, the process of offshore off-grid hydrogen production is outlined, and two alternative electrolyzer configurations are

proposed for the hydrogen production stage. Subsequently, a time-series simulation-based technical performance model is developed to represent offshore wind power generation and wind-to-hydrogen conversion. In this model, the electrolyzer module incorporates the dynamic operating strategy, enabling the system's dynamic response under specified input conditions to be accurately characterized, which is consistent with the actual behavior of electrolyzer operation. Based on the optimized electrolyzer capacity derived from the performance model, a real options analysis framework is then established to support the investment decision-making for offshore off-grid hydrogen projects. The model introduces learning curves to represent cost reductions associated with technological progress and uses stochastic processes to describe the major market uncertainties that influence the project value. The dynamic optimization problem is solved using the least squares Monte Carlo method, through which the project's optimal investment timing and investment value are obtained. In addition, a sensitivity analysis is performed on key uncertainty parameters.

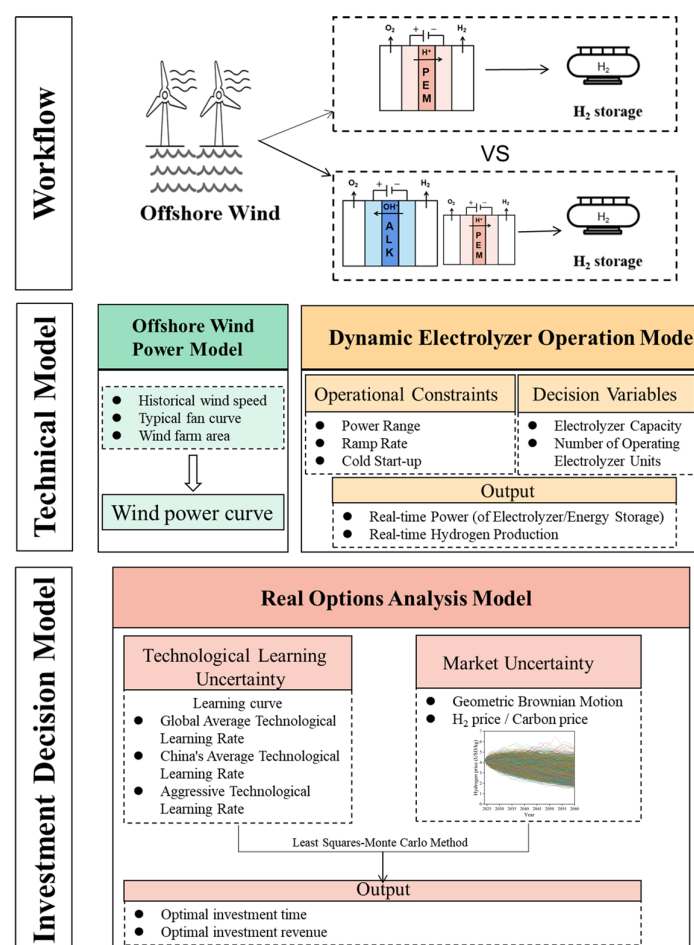


Figure 1. Research framework.

2.1. Offshore Wind Power Simulation

Because wind farm output profiles are highly confidential and cannot be accessed directly, this study extracts historical wind speed data from 2002 to 2023 from the global reanalysis dataset ERA5 and simulates annual offshore wind generation in Guangdong Province, using the power curve of a representative turbine. The detailed methodology has been documented in our previous work [26].

2.2. Time-Series-Based Dynamic Model of the Hybrid Electrolyzer Configuration

After offshore wind power is converted to electricity, it is supplied to the offshore platform for off-grid hydrogen production. The proposed ALK–PEM hybrid electrolyzer configuration requires attention to two aspects. First, in the hydrogen production stage, multiple electrolyzer units operate in combination, and the stable operation of each unit must be ensured. Second, the operational stability of ALK electrolyzers under fluctuating wind power is of particular concern. In this study, the stable operation of electrolyzers is characterized by three conditions: the permissible power-load range, the ramping rate, and the cold-start requirement [27].

The PEM electrolyzer operates across approximately 0–100% of its rated capacity, while ALK operates within roughly 20–100% of its rated capacity [28]. When the input power falls below the minimum load, the oxygen content in hydrogen may rise rapidly, creating an explosion risk, and the electrolyzer must be shut down. In this study, the minimum load of the combined electrolyzer system is defined as the product of the minimum load of a single unit and the number of units.

Regarding the ramping rate—the allowable rate of power adjustment—ALK electrolyzers typically operate within 1–5% of the rated power per minute, which is significantly lower than PEM’s 10–20% of the rated power per second. The limited dynamic response of ALK is the main reason it cannot independently accommodate variable wind power; integrating PEM or storage can effectively support ALK under fluctuating power input. When wind power increases abruptly and exceeds ALK’s ramp-up limit, the excess power is allocated to the PEM electrolyzers. When wind power drops sharply and falls below ALK’s ramp-down limit, the storage must discharge to support ALK as it gradually reduces its hydrogen production load until it aligns with real-time wind power.

With respect to cold-start characteristics, PEM electrolyzers also outperform ALK units. In practice, when the wind power suddenly increases and hydrogen production must be initiated, ALK requires approximately one hour of preheating before hydrogen generation can begin. During ALK’s cold-start period, PEM electrolyzers are engaged to maintain hydrogen production and avoid wasting the available wind power.

Based on the above considerations, this study develops a time-series model to calculate hydrogen production for the hybrid electrolyzer configuration. The model takes a wind-power time series with a 15 min resolution as input, totaling 35,040 time steps per year, and outputs the system’s annual hydrogen production M_H . The single-unit capacity of the PEM electrolyzer is assumed to be 1 MW. The main decision variables of the model include the total installed ALK capacity Q^{ALK} , the maximum number of operating ALK units N^{ALK} , and the total installed PEM capacity Q^{PEM} . At each time step t , the input wind power P_t^{wind} is allocated among the electrolyzer power consumption, storage power, and curtailed power.

$$P_t^{wind} = P_t^{ALK} + P_t^{PEM} + P_t^{st} + P_t^c \quad (1)$$

- (1) Power allocation to ALK electrolyzers. The system first allocates the available wind power P_t^{wind} to ALK units. The allocated power P_t^{ALK} and the maximum number of operating ALK units N^{ALK} are given by the following:

$$P_t^{ALK} = \min(P_t^{wind}, Q^{ALK}) \quad (2)$$

$$N^{ALK} = \left\lfloor \frac{Q^{ALK}}{P_{rated}^{ALK}} \right\rfloor \quad (3)$$

If the input power exceeds the total ALK capacity, the excess is allocated to the PEM until all electrolyzers reach their rated operating conditions; any remaining power is

treated as curtailment. Let the theoretical number of operating ALK units at time t be $N_t^{ALK,th}$. Then,

$$N_t^{ALK,th} = \begin{cases} N_t^{ALK}, & P_t^{ALK} > N_t^{ALK} \cdot P_{\min}^{ALK} \\ \left\lfloor \frac{P_t^{ALK}}{P_{\min}^{ALK}} \right\rfloor, & \text{otherwise} \end{cases} \quad (4)$$

- (2) Start-up, shutdown, and ramping characteristics of ALK units. To avoid frequent start-ups and shutdowns, when the input power decreases, the corresponding ALK units are shut down; when the input power increases, new units are gradually started only after the operating units reach a full load. The actual number of operating ALK units is as follows:

$$N_t^{ALK} = \begin{cases} N_t^{ALK,th}, & N_t^{ALK,th} < N_{t-1}^{ALK} \\ \left\lfloor \frac{P_t^{ALK}}{P_{rated}^{ALK}} \right\rfloor, & P_t^{ALK} > N_{t-1}^{ALK} \cdot P_{rated}^{ALK} \\ N_{t-1}^{ALK}, & \text{otherwise} \end{cases} \quad (5)$$

Newly started ALK electrolyzers must go through a cold-start phase of four time steps. After completing the cold-start phase, the power gradually ramps up until it matches either the power of the main operating phase or the rated capacity.

Let the state variable $N_t^{cold,k}$ denote the number of ALK units in the k -th stage of cold start ($k = 1, \dots, 4$), $N_t^{ramp,m}$ denote the number of ALK units in the m -th stage of ramping ($m = 1, \dots, 4$), and $N_t^{ALK,run}$ denote the number of ALK units actively operating in the main system.

At time t , the number of ALK units requiring a cold start is as follows:

$$\Delta N_t^{ALK,start} = \max(N_t^{ALK} - N_{t-1}^{ALK}, 0) \quad (6)$$

During an ALK cold start,

$$N_t^{cold,1} = \Delta N_t^{ALK,start} \quad (7)$$

$$N_t^{cold,k} = N_{t-1}^{cold,k-1} \quad (8)$$

ALK units that have completed a cold-start phase enter the ramping phase:

$$N_t^{ramp,1} = N_{t-1}^{cold,4} \quad (9)$$

Ramping must account for the number of electrolyzers D_t^m dynamically merged into the main operating phase:

$$N_t^{ramp,m} = N_{t-1}^{ramp,m-1} - D_t^{m-1} \quad (10)$$

The rules for dynamically merging electrolyzers are as follows: first, the average power of the main operating pool is calculated:

$$\bar{P}_t^{ALK} = \min \left(\max \left(\bar{P}_{t-1}^{ALK} - P_{unit}^{ALK}, \frac{P_t^{ALK} - \sum_{m=1}^6 (P_t^{ramp,m} \cdot N_t^{ramp,m})}{N_t^{ALK,run}} \right), \bar{P}_{t-1}^{ALK} + P_{unit}^{ALK} \right) \quad (11)$$

Next, the highest ramping stage eligible for merging is determined:

$$m_t^* = \max \left\{ m \in [1, 6] : P_t^{ramp,m} \leq \bar{P}_t^{ALK} \right\} \quad (12)$$

The number of ALK units merged at each stage and the actual number of operating ALK units are given by the following:

$$D_t^m = \begin{cases} N_{t-1}^{ramp,m}, \forall m \leq m_t^* \\ 0, \forall m > m_t^* \end{cases} \quad (13)$$

$$N_t^{ALK,run} = \begin{cases} N_t^{ALK}, N_t^{ALK} \leq N_{t-1}^{ALK,run} \\ N_{t-1}^{ALK,run} + \sum_{m=1}^{m_t^*} D_t^m, otherwise \end{cases} \quad (14)$$

- (3) Power allocation to PEM electrolyzers. The PEM configuration handles two components of power: compensating for the power exceeding the ALK units' limits during a cold start, and absorbing the surplus wind power that exceeds the ALK system capacity.

The portion of ALK power exceeding the limit is calculated as follows:

$$P_t^{ALK,over} = \max(\bar{P}_t^{ALK} - P_t^{ALK,unit}, 0) \cdot N_t^{ALK,run} \quad (15)$$

The number of PEM units required to compensate for the excess power is as follows:

$$N_t^{PEM,comp} = \lceil P_t^{ALK,over} \rceil \quad (16)$$

The total capacity of the PEM electrolyzers is as follows:

$$Q^{PEM} = \max_t(N_t^{PEM,comp}) \quad (17)$$

- (4) Energy storage power allocation. The role of energy storage discharging is twofold: first, to supply the power required for an ALK cold start, and second, to provide the power needed for the safe ramp-down of ALK units that are cut out from operation.

$$P_t^{st} = P_t^{ramp-down} + P_t^{start-up} \quad (18)$$

Energy storage charges when there is surplus wind power and the storage is not fully charged.

$$P_t^{st,ch} = \min(P_t^c, Q^{st}) \quad (19)$$

- (5) Hydrogen production calculation. When PEM operates to compensate for ALK power exceeding its limits, the hydrogen production is as follows:

$$M_t^{PEM,comp} = f_P\left(\frac{P_t^{ALK,over}}{N_t^{PEM,comp}}\right) \cdot N_t^{PEM,comp} \cdot \Delta t \quad (20)$$

where $f_P(x)$ is the hydrogen production function of the PEM electrolyzers.

The number of PEM units operating to consume regular wind power is as follows:

$$N_t^{PEM,wind} = \min(Q^{PEM}, P_t^{wind} - P_t^{ALK}) \quad (21)$$

The hydrogen production from PEM units used to absorb the surplus wind power exceeding ALK capacity is as follows:

$$M_t^{PEM,wind} = f_P\left(\frac{P_t^{wind} - P_t^{ALK}}{N_t^{PEM,wind}}\right) \cdot N_t^{PEM,wind} \cdot \Delta t \quad (22)$$

The total hydrogen production of the PEM configuration is as follows:

$$M_t^{PEM} = M_t^{PEM,comp} + M_t^{PEM,wind} \quad (23)$$

The total hydrogen production of the ALK configuration is as follows:

$$M_t^{ALK} = f_A \left(\min \left(\bar{P}_t^{ALK}, P_t^{ALK,unit} \right) \right) \cdot N_t^{ALK,run} \cdot \Delta t \quad (24)$$

The system's annual total hydrogen production is as follows:

$$M_H = \sum_{t=1}^T \left(M_t^{ALK} + M_t^{PEM} \right) \quad (25)$$

- (6) Beyond the operational constraints described above, the model also limits wind curtailment to a certain range, based on the actual renewable power consumption in the local grid.

$$\eta = \frac{\sum P_t^c}{\sum P_t^{wind}} \leq \eta_{\max} \quad (26)$$

2.3. Electrolyzer Capacity Optimization and Real Options Model

A larger electrolyzer capacity enables greater utilization of wind power, resulting in higher hydrogen production and hydrogen sales revenue; however, it also leads to higher costs. Therefore, it is necessary to establish an optimization model for electrolyzer capacity, with the objective of maximizing hydrogen production profit.

Assuming that the hydrogen production project is invested in the base year t_0 , the objective function is as follows:

$$\max Z = \max \left[\sum_{i=t_0+1}^{t_0+LC} e^{-r(i-t_0)} \times CF_i - C_i \right] \quad (27)$$

where CF denotes the net cash flow during the project's operation period, including hydrogen sales revenue, carbon reduction revenue, and operation and maintenance (O&M) costs; C denotes the project cost; LC denotes the project lifetime; and r is the discount rate.

$$CF = u_h \times \sum M_h + u_c \times \varepsilon \times \sum M_h - C_{EOM} - C_{HOM} \quad (28)$$

$$C = C_{EI} + C_{HI} \quad (29)$$

where u_h denotes the hydrogen price, u_c is the carbon price, ε is the carbon reduction factor, C_{EOM} is the wind farm O&M cost, C_{HOM} is the hydrogen production O&M cost, C_{EI} is the wind farm investment cost, and C_{HI} is the hydrogen production investment cost.

$$C_{EI} = c_f P_f \quad (30)$$

$$C_{EOM} = \alpha_f c_f P_f \quad (31)$$

$$C_{HI} = c_e P_e + c_{st} P_{st} + c_k n_k \quad (32)$$

$$C_{HOM} = \alpha_e c_e P_e + \alpha_{st} c_{st} P_{st} + \alpha_k c_k n_k \quad (33)$$

In the formula, c represents the unit investment cost, P the corresponding capacity, and n the corresponding quantity. The subscripts f , e , st , and k represent wind power installation, electrolyzer, energy storage, and the spherical hydrogen storage tank, respectively.

Regarding the constraints, the dynamic operation model in Section 2.2 must be satisfied, including the power balance constraint, the electrolyzer start-up and ramping constraints, integer constraints, etc., as described in the equations in Section 2.2.

The discounted cash flow method evaluates the economic viability of the project, whereas the real options method evaluates the maximum project value and determines the optimal investment timing. The project value PV_t of an off-grid offshore wind-to-hydrogen project invested in year t during its lifecycle is expressed as follows:

$$PV_t = E \left[\sum_{i=t+1}^{t+LC} e^{-r(i-t)} \times CF_i - C_t \right] \quad (34)$$

where E represents the expectation.

The project's best investment value TIV is expressed as follows:

$$TIV = \max(PV_{t_s} \times e^{-rt_s}, 0) \quad (35)$$

where t_s is the optimal investment time.

This study employs the least squares Monte Carlo method for the solution. The basic idea is to generate the cross-sectional data of price sample paths through a random simulation, then solve it backward from the expiration time. Least squares regression is used to obtain the option holding value at each time, which is compared with the intrinsic value to determine the option value and the optimal exercise time for each sample path. Finally, the option values of all samples are discounted using the risk-free rate and averaged to obtain the optimal option value [29].

2.4. Uncertainty Analysis

The uncertainties examined in this study refer to the factors that affect the economic performance of offshore wind-to-hydrogen projects, with a primary focus on uncertainties in technological advancement and the market environment.

2.4.1. Technological Progress

Considering that both offshore wind power and electrolytic hydrogen production are currently undergoing rapid development, their future investment costs will further decline. Therefore, a technological learning curve is introduced to capture this change.

$$C_t = C_0 \times \left(\frac{Q_t}{Q_0} \right)^b \quad (36)$$

$$LR = 1 - 2^b \quad (37)$$

where C_t and C_0 represent the investment costs in year t and the base year, respectively; Q_t and Q_0 represent the cumulative installed capacities in year t and the base year, respectively; and b denotes the technological progress rate.

2.4.2. Uncertainty in Market Prices

For offshore wind-to-hydrogen projects, the economic revenue includes not only hydrogen sales but also carbon reduction income derived from selling China certified emission reductions (CCERs) in China's carbon market. It is assumed that prices follow a geometric Brownian motion stochastic process [30], as expressed by the following equation:

$$dx_t = \mu x_t dt + \sigma x_t dz \quad (38)$$

$$\mu = \frac{\overline{\ln\left(\frac{x_t}{x_{t-1}}\right)}}{\Delta t} \quad (39)$$

$$\sigma = \sqrt{\frac{\frac{1}{n-2} \sum_{t=1}^{n-1} \left[\ln\left(\frac{x_t}{x_{t-1}}\right) - \overline{\ln\left(\frac{x_t}{x_{t-1}}\right)} \right]^2}{\Delta t}} \quad (40)$$

where x represents the carbon price, μ the price drift rate, σ the price volatility, dz the standard Wiener process, Δt the time interval, and n the number of observed samples.

3. Case Study

The offshore wind farm selected for this study is located in a planned wind power zone, approximately 100 km off the coast of Guangdong Province. The wind farm has an installed capacity of 1000 MW, and its simulated power output curve is shown in Figure 2.

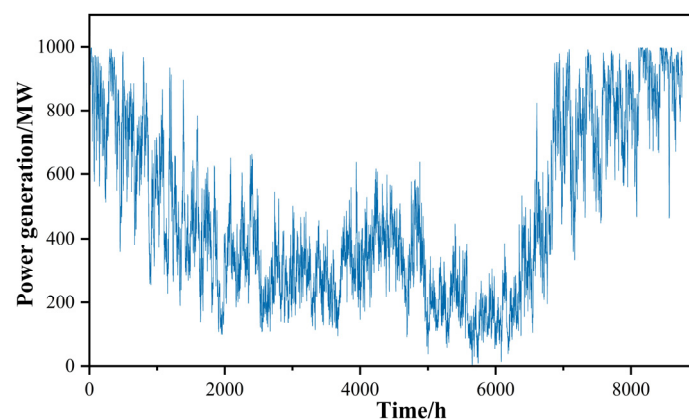


Figure 2. Guangdong Province offshore wind farm annual generation curve.

The hydrogen production efficiency of electrolyzers varies with the input power, creating a nonlinear relationship between the input power and the hydrogen production of the electrolyzers. For computational convenience, we linearize the production curves of the electrolyzers with reference to [31,32], as shown in Figure 3. It should be noted that the unit capacities of the electrolyzers are set based on the prevailing specifications in current Chinese hydrogen production practice: the unit capacity of ALK electrolyzers is set to 5 MW, while that of PEM electrolyzers is set to 1 MW, which is consistent with the standard configurations that are widely adopted in domestic large-scale projects.

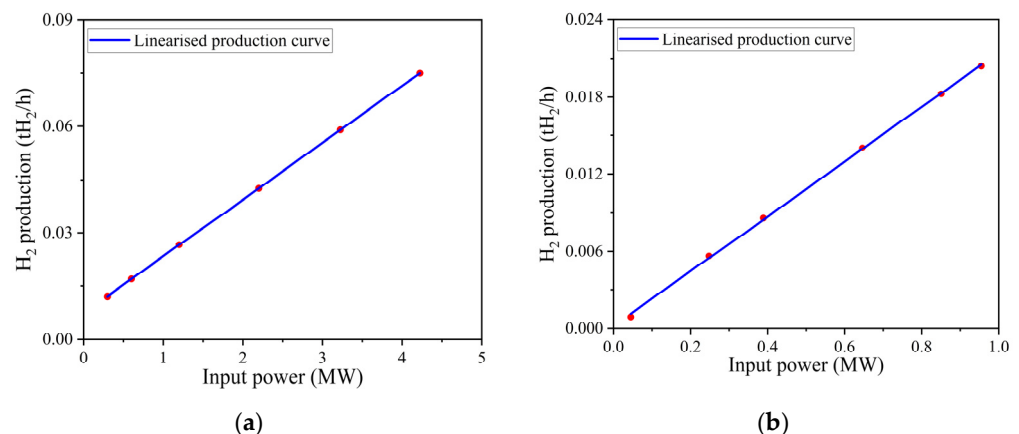


Figure 3. Hydrogen production curve. (a) ALK electrolyzer and (b) PEM electrolyzer.

The project construction period is assumed to be 2 years, and the operation period is 20 years. The investment decision-making period selected in this study is 15 years, with 2025 set as the base year. We comprehensively collect the basic data required for model calculations, which rely on various techno-economic parameters, including the unit costs of different components. The specific parameters used are listed in Table 3. In addition, this study adopts the average 2024 exchange rate published by the People's Bank of China (1 USD = 7.12 CNY) for currency conversion.

Table 3. Key economic and technical assumptions used in this study.

Economic and Technical Assumptions	Symbol	Value	Unit	Reference
Investment decision period of project		15	years	Defined in this study
Project period		20	years	
Discounted rate		5%		
Unit investment cost of far-offshore wind farm	c_f	1,685,393	USD/MW	[33]
Unit investment cost of electrolyzer (ALK/PEM)	c_e	280,899/842,696	USD/MW	[33]
Unit investment cost of energy storage	c_{st}	210,674	USD/MWh	[34]
Unit investment cost of spherical hydrogen storage tank	c_k	561,797	USD/unit	[33]
Fixed O&M cost factor of far-offshore wind farm	α_f	5%		Defined in this study
Fixed O&M cost factor of electrolyzer	α_e	10%		
Fixed O&M cost factor of energy storage	α_{st}	5%		
Fixed O&M cost factor of spherical hydrogen storage tank	α_k	5%		
Maximum rate of wind curtailment	$\eta_{\max}$	0.1%		[35]
Carbon reduction factor for electrolytic hydrogen	ε	19	kgCO ₂ /kgH ₂	[36]

For the calculation of technological progress, this study refers to China's domestic offshore wind and electrolyzer installed capacity and the average construction cost data since 2010, and, following [18,37,38], sets up three scenarios with low, medium, and high technological learning rates—S1, S2, and S3. Scenario S1 represents the global average technological progress (low-speed scenario), S2 represents the domestic average technological progress over the past decade (medium-speed scenario), and S3 represents a high-speed progress scenario defined in this study. The learning rate here is defined as the fractional reduction in unit capital cost for each doubling of cumulative installed capacity, and is expressed as a dimensionless value. Higher learning rates correspond to faster cost reductions under more optimistic technological progress assumptions. The specific parameters are shown in Table 4.

Table 4. Scenario settings for technological progress.

Scenario	Components	Learning Rate
S1	Far-offshore wind farm	0.14
	Electrolyzer	0.12
S2	Far-offshore wind farm	0.18
	Electrolyzer	0.18
S3	Far-offshore wind farm	0.20
	Electrolyzer	0.24

For the calculation of market price uncertainty, the parameters used and assumed in this study are listed in Table 5, below. Specifically, the drift rate represents the expected annual percentage change in price (positive = upward trend, negative = downward trend), while the volatility represents the annual standard deviation of price fluctuations, which are both expressed as dimensionless fractions. The drift rate and volatility are mainly derived from our reference to historical data over the past decade.

Table 5. Parameter settings related to price uncertainty.

Parameter	Value	Unit	Reference
2024 Green hydrogen price	4.22	USD/kgH ₂	[39]
2024 CCER carbon price	12.64	USD/tCO ₂	[40]
Hydrogen price drift rate	−0.01		Set by this study
Hydrogen price volatility	0.03		
CCER carbon price drift rate	0.02		
CCER carbon price volatility	0.03	USD/kgH ₂	

Figure 4 illustrates 10,000 simulated paths of hydrogen and carbon prices generated from the geometric Brownian motion used in this study.

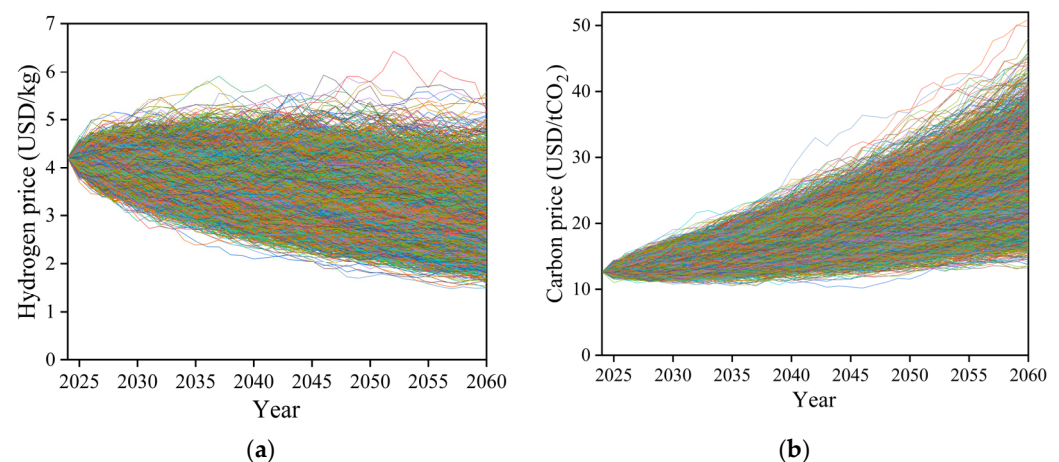


Figure 4. Simulated paths of (a) hydrogen price and (b) carbon price.

As shown in Figure 4a, the simulated hydrogen price paths display a gradual declining trend with moderate volatility, which is consistent with the expected cost reductions driven by technological learning. The carbon price paths in Figure 4b exhibit an upward drift, reflecting the anticipated strengthening of carbon pricing policies.

4. Results and Discussion

4.1. Operational Results of the Hybrid Electrolyzer Configuration

Using the above model, we compute the minimum levelized hydrogen production cost and the optimal electrolyzer capacity configuration for the ALK–PEM hybrid configuration and the standalone PEM configuration under the objective of maximizing hydrogen production revenue, as shown in Table 6. Taking the baseline-year cost parameters as an example, compared with the standalone PEM configuration, the ALK–PEM hybrid configuration—while producing a slightly lower hydrogen output under the required operating strategy—can significantly reduce the investment and operating costs of the offshore wind-to-hydrogen project. Over the project lifetime, the hybrid configuration yields an average unit hydrogen production cost that is approximately 15% lower than that of the standalone PEM configuration.

Table 6. Comparison of operating results for the two electrolyzer configurations.

	Unit	Standalone PE840	Hybrid
ALK capacity	MW	/	840
PEM capacity	MW	970	134
Battery storage capacity	MWh	7	313
Lifecycle cost (including wind power)	million USD	4676.24	3724.96
Annual hydrogen production	t/a	74,590	70,330
Lifecycle average levelized hydrogen production cost (including wind power)	USD/kg	3.13	2.65
Wind curtailment rate	%	0.1	0.083

Figure 5 illustrates the detailed operational performance of the hybrid electrolyzer configuration. Heatmap Figure 5a shows the time-varying load factors of the electrolyzers, where the ALK electrolyzer exhibits an annual average load factor of approximately 55%, and the PEM electrolyzer exhibits an annual average load factor of about 10%. Combined with panels Figure 5b,c, which show the variation in the number of operating electrolyzer units, and panel Figure 5d, which shows the state of charge of the energy storage system, the following observations can be made:

- (1) During the high-wind season from October to March, the electrolyzers operate at relatively high load factors. The ALK load factor is around 76%. Due to frequent sudden increases in wind power, ALK cannot always absorb the full wind power output, requiring the PEM electrolyzer to undertake part of the wind-power utilization. The PEM load factor is approximately 18%.
- (2) During the low-wind season from April to September, the ALK load factor is approximately 33%. In this period, ALK can absorb most of the available wind power, and almost no additional PEM operation is required, with the PEM load factor remaining below 1%. However, sudden drops in wind power frequently occur during the low-wind season; the energy storage system therefore needs to discharge to support the ramp-down requirement of ALK, ensuring the safe operation of the electrolyzers.
- (3) The energy storage system charges using surplus wind power during the high-wind season at the beginning of the year and discharges during the low-wind season to support ALK operation. In the high-wind season at the end of the year, the presence of PEM for power regulation means that almost no additional charging is required.

4.2. Optimal Investment Timing and Investment Value

Figure 6 illustrates the investment value and optimal investment timing of off-grid offshore wind-powered hydrogen production projects under three technological learning scenarios and two electrolyzer configurations. Under the conventional NPV framework, all scenarios—whether learning rates remain at the global average (S1, low-speed), the domestic average over the past decade (S2, medium-speed), or a higher rate (S3, high-speed)—result in negative investment returns ($NPV < 0$) for both the hybrid configuration and the standalone PEM configuration. Under current technological and cost conditions, immediate investment is therefore not financially justifiable based on conventional NPV analysis alone. This finding provides a rational explanation, from an investment perspective, for why large-scale commercial deployment of offshore wind-to-hydrogen has remained limited to date.

When adopting the real options framework, incorporating the option to delay investment increases the project value. For the standalone PEM configuration, if the learning rates for offshore wind and electrolyzers remain slow (S1), the optimal investment year is 2039, with an investment value of only USD 23.4 million—substantially lagging behind

the other scenarios. This indicates that the current global pace of technological progress in offshore wind and electrolyzers is insufficient to support the future development of hydrogen production projects. As the learning rates increase, and future technological improvement maintains or exceeds recent domestic levels (S2 or S3), the optimal investment year advances to 2035 or 2033, with investment values of approximately USD 540 million or USD 700 million, respectively.

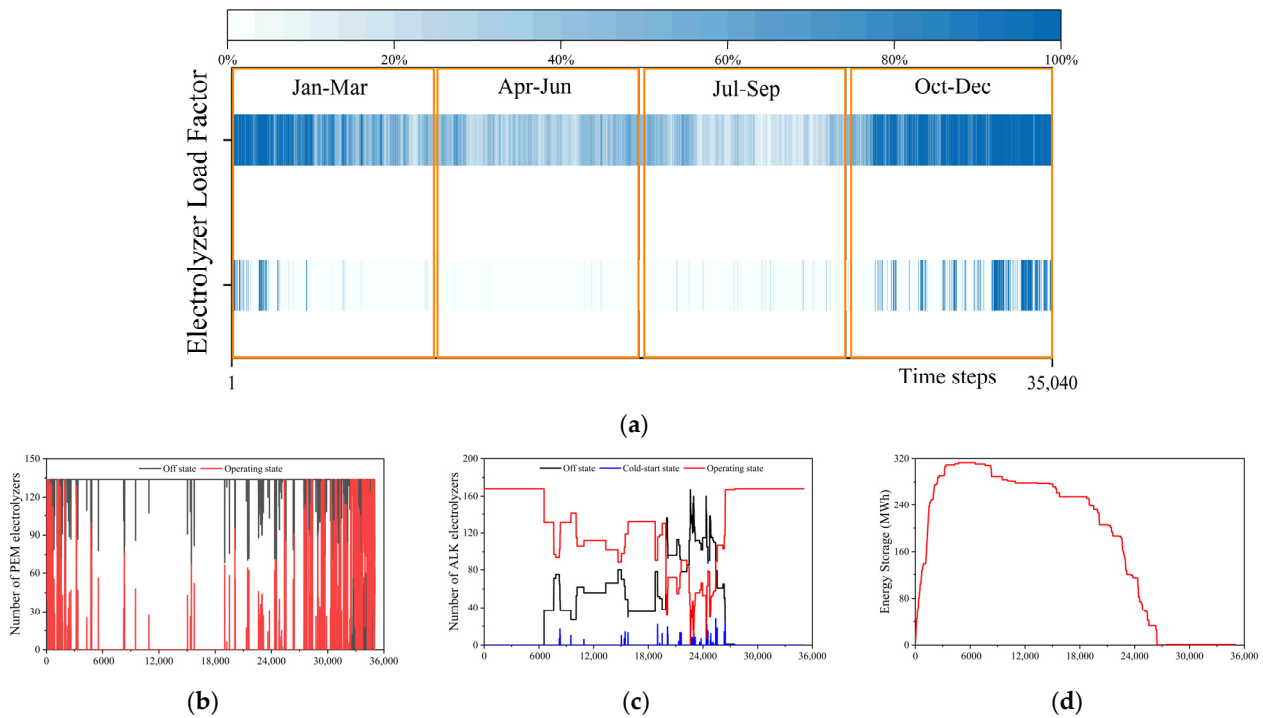


Figure 5. Operational performance of the hybrid electrolyzer configuration. (a) Heat map of hybrid electrolyzer load factor; (b) dynamic start-stop profile of the PEM electrolyzer; (c) dynamic start-stop profile of the ALK electrolyzer; and (d) energy variation profile of the energy storage system.

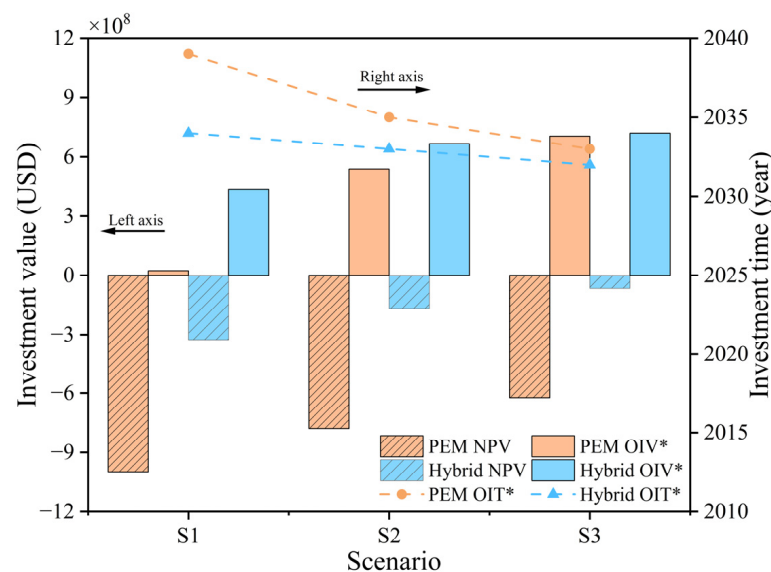


Figure 6. Investment decisions for hybrid and PEM electrolyzers under three scenarios. * OIT and OIV denote optimal investment timing and optimal investment value.

For the hybrid electrolyzer configuration, the results show consistently higher investment values and earlier investment timings compared with the standalone PEM configura-

tion. Under the slow-learning scenario S1, incorporating ALK significantly enhances the project value—by a factor of 18, relative to the standalone PEM case—and advances the optimal investment year to 2034. Notably, the investment value of the hybrid configuration is less sensitive to increases in learning rates: in both the S2 and S3 scenarios, the optimal investment timing stabilizes around 2032, and the investment value remains within the range of USD 660–720 million. Therefore, when technological progress is slow (S1 or S2), the hybrid configuration offers a significantly higher investment value and earlier investment timing than the standalone PEM configuration, supporting faster development of offshore wind hydrogen projects. When technological progress is rapid (S3), the two configurations yield comparable optimal investment values.

4.3. Sensitivity Analysis

Within the real options framework, the parameter settings of the stochastic processes have a critical impact on investment decisions. In this study, the hybrid electrolyzer configuration is used as the target for sensitivity analysis, focusing on the drift rates and volatilities of green hydrogen and carbon prices, as well as the project discount rate.

The effects of hydrogen and carbon price drift rates and volatilities on the investment probability distribution are shown in Figure 7. The analysis indicates that the drift rate of green hydrogen prices has a significant impact on the optimal investment timing and investment value. A lower drift rate reflects stronger expectations of accelerated price decline. As the hydrogen price drift rate gradually decreases, the probability distribution curve shifts to the right, delaying the optimal investment timing while reducing the investment value. When the drift rate drops from -1% to -2% , the optimal investment timing is postponed from 2034 to 2036, and the investment value decreases by 64%. Conversely, if the drift rate rises to -0.1% , the investment value increases by 58%. Changes in hydrogen prices imply variations in project revenue; although declining hydrogen prices may promote green hydrogen consumption, from the investor's perspective, rapid decline in product market profit increases the project risk, discouraging investment and making investors more likely to delay investment. On the other hand, the volatility of hydrogen prices has a relatively weak effect on the optimal investment timing, but it increases both the investment probability and investment value at the optimal investment time. When the price volatility decreases from 3% to 1%, the stabilization of hydrogen prices significantly raises the probability of investment in 2034.

Compared with hydrogen prices, the drift rates and volatilities of carbon prices have a minor impact on the investment probability distribution curve. When the drift rate increases from 2% to 4%, the optimal investment timing remains unchanged, and the investment value rises by 12%; changes in volatility have almost no effect on either the investment timing or value.

The effect of the discount rate on investment decisions is shown in Figure 8. When the discount rate is 2%, the investment value of the offshore wind hydrogen production project reaches its maximum, at USD 1.15 billion; when the discount rate is 3%, the optimal investment timing is at its earliest, in 2032. As the discount rate gradually increases, the project's investment value steadily decreases, and the optimal investment timing is progressively delayed. When the discount rate rises to 8%, the investment value drops to USD 40 million, and the optimal investment timing is postponed to 2040. For long-term projects such as offshore wind hydrogen production, a high discount rate implies greater uncertainty for future returns and lower attractiveness, which reduces investors' confidence in the project's future and delays the investment timing.

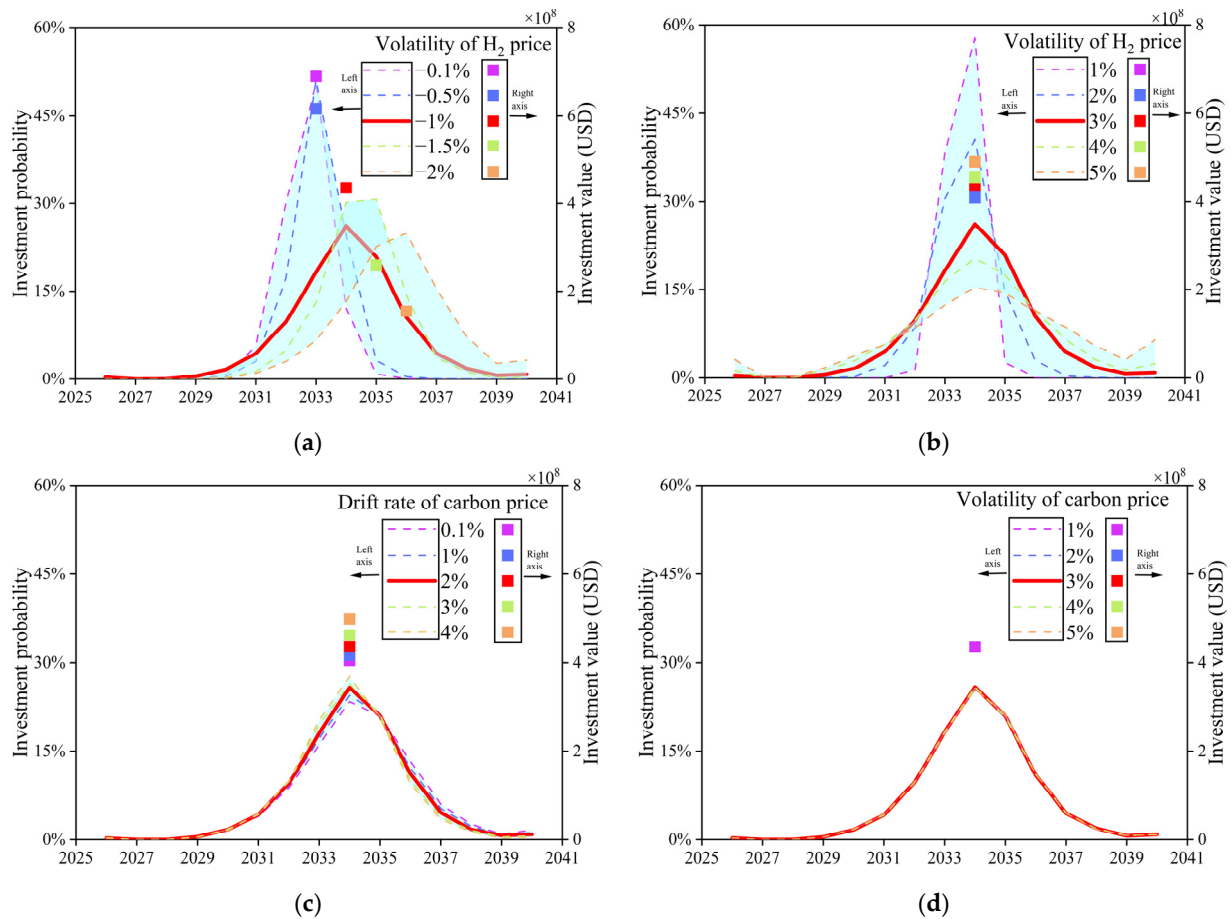


Figure 7. Sensitivity analysis of simulation parameters. (a) Drift rate of H_2 price. (b) Volatility rate of H_2 price. (c) Drift rate of carbon price. (d) Volatility of carbon price.

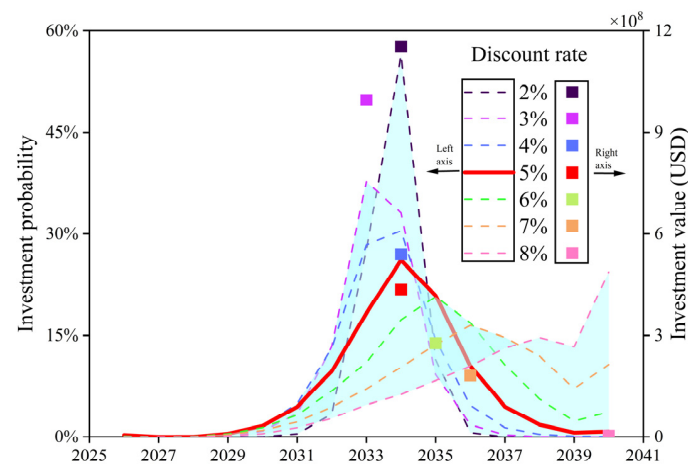


Figure 8. Sensitivity analysis of discount rate.

5. Conclusions

This study develops an analytical framework that integrates a dynamic operational model for a hybrid electrolyzer configuration with real options theory to evaluate both the investment value and the optimal investment timing of an off-grid offshore wind-to-hydrogen project. The main findings are summarized as follows:

- (1) The hybrid ALK–PEM configuration achieves a more economically efficient allocation of costs and renewable resources through coordinated operation, outperforming the standalone PEM configuration in overall economic performance. A detailed examina-

tion of system operations shows that the low-cost ALK electrolyzer handles most of the stable power input—particularly during high-wind seasons—resulting in a high annual capacity factor. In contrast, the high-cost but fast-response PEM electrolyzer is precisely allocated as a regulating unit, primarily functioning as a “peak-shaving” device to absorb volatile power exceeding the ALK’s processing capability. This division of roles maintains safe operation and low curtailment while enabling optimal capital allocation. The case study results further confirm the economic advantage of the hybrid configuration: under identical operational constraints, the hybrid ALK–PEM configuration (840 MW ALK + 134 MW PEM), compared with the standalone PEM configuration (970 MW PEM), slightly reduces the annual hydrogen production (from 74,590 t to 70,330 t) due to the ALK’s restricted load-following capability. However, benefiting from the lower capital cost of ALK electrolyzers, the hybrid system achieves a lower total lifecycle investment and operating cost, ultimately reducing the levelized cost of hydrogen from 3.13 USD/kg to 2.65 USD/kg, a decrease of approximately 15%. This demonstrates that integrating operational strategies into capacity planning—particularly by incorporating low-cost ALK electrolyzers—offers a viable and effective pathway for reducing the levelized cost of hydrogen in off-grid offshore wind-to-hydrogen systems.

- (2) Real options analysis reveals an investment value that is obscured under the traditional NPV framework. Within a standard discounted-cash-flow assessment, all scenarios yield negative net present values, leading to the conclusion that the project is not currently economically viable. In contrast, the real options model quantifies the value of “waiting” as a strategy to cope with uncertainty. The results indicate that, across different technological-progress scenarios, the optimal investment window for the hybrid ALK–PEM configuration falls between approximately 2032 and 2034. Under the low-progress (S1) and medium-progress (S2) scenarios, the hybrid configuration not only delivers substantially higher investment value than the standalone PEM configuration, but also exhibits a markedly earlier optimal investment timing. This demonstrates that, at the current stage when technology costs remain relatively high, adopting the hybrid configuration offers a more resilient and economically favorable pathway. In the idealized high-progress scenario (S3), however, the investment values of the two configurations converge, implying that if PEM costs decline rapidly, its operational flexibility will offset its cost disadvantage, rendering both configurations competitive in the future.
- (3) Hydrogen price expectations and capital costs are the two most influential external factors shaping investment decisions. Sensitivity analysis shows that the hydrogen price drift rate—representing the expected trend of price increase or decrease—has the most pronounced impact on both investment timing and value. A stronger expected decline in hydrogen prices leads investors to delay investment. Meanwhile, the discount rate, representing capital costs, has a substantial negative effect: an increase in the discount rate significantly reduces the long-term project value and postpones the optimal investment year. In comparison, carbon price variation—within the currently assumed parameter range—has a more limited impact on decision outcomes; nevertheless, its long-term upward potential remains a critical source of value for the project.

Based on the above findings, this study proposes several policy recommendations. First, technological retrofits and cost-reduction research and development for ALK electrolyzers under variable renewable power conditions should be supported, alongside integrated innovation and demonstration projects that combine ALK and PEM electrolyzers into hybrid systems. Such measures can lower hydrogen production costs at the

technological source. Second, a stable market outlook and price support mechanism for green hydrogen should be established. Policy tools such as long-term green hydrogen procurement agreements and contracts for difference can provide stable price signals and revenue certainty, effectively mitigating early-stage investment risks. Third, given the sensitivity of investment outcomes to the discount rate, financial institutions should be encouraged to offer preferential-rate loans. Finally, the carbon market's incentive function should be progressively enhanced by ensuring that carbon prices follow a reasonable upward trajectory and by facilitating the entry of emission-reduction credits from green hydrogen projects into the market.

Despite the efforts to ensure rigor, this study has several limitations. First, although the electrolyzer operation model is relatively detailed, the efficiency curves are still linearized, and the storage model remains simplified. Future research may incorporate degradation models to more accurately simulate the evolution of electrolyzer and storage efficiency over time. Second, this study considers only two investment strategies—immediate investment and delayed investment. In practice, however, investors often adopt more flexible strategies, such as phased investment: implementing a small-scale pilot in the early stages and deciding whether to scale up once market uncertainty declines or the technology matures. Such compound-option strategies, which embed “growth options” and “scaling flexibility,” can better capture managerial flexibility in real-world conditions. Developing an extended model that incorporates multi-stage investment decisions thus represents an important and valuable direction for future research. Third, the current system boundary does not account for the freshwater supply, which is a significant practical concern in far-offshore hydrogen production, as PEM electrolyzers require high-purity deionized water as feedstock. Recent studies have highlighted the importance of integrating desalination or freshwater delivery infrastructure into renewable hydrogen systems [41,42]. Incorporating the freshwater supply into the system boundary thus represents an important direction for future research.

Author Contributions: Conceptualization, H.L. and Q.T.; methodology, H.L. and Q.T.; software, H.L.; validation, H.L., Q.T., S.Z. and C.L.; formal analysis, H.L.; investigation, H.L. and Q.T.; resources, H.L.; data curation, H.L.; writing—original draft preparation, H.L. and Q.T.; writing—review and editing, Q.T. and C.L.; visualization, H.L.; supervision, Q.T., S.Z. and C.L.; project administration, Q.T. and C.L.; funding acquisition, Q.T. and S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (72374122).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Liu, X.; Han, X.; Qin, M. Current status of floating wind power technology and prospects for China's deep sea wind power development. *China Offshore Oil Gas* **2024**, *36*, 233–242.
2. Zhao, L.; Wei, C.; Wang, Y.; Qiu, Y.; Dong, F. Macroscopical Site Selection and Estimation of Wind Energy Reserves for Offshore Wind Farms. *Acta Energiæ Solaris Sin.* **2024**, *45*, 1–8.
3. Li, Z.; Hu, P.; Ma, J.; Gao, M.; Huang, H.; Liu, X.; Qi, L.; Sun, Z. Analysis and prospect of offshore wind power development in China. *China Offshore Oil Gas* **2022**, *34*, 229–236.
4. van Stralen, J.; Janssen, G.; Koornneef, J.; Scheepers, M.; Sipma, J.; van der Zwaan, B. Prospects for offshore hydrogen production in the Netherlands. *Environ. Res. Energy* **2025**, *2*, 015014. [[CrossRef](#)]
5. Ramakrishnan, S.; Delpisheh, M.; Convery, C.; Niblett, D.; Vinothkannan, M.; Mamlouk, M. Offshore green hydrogen production from wind energy: Critical review and perspective. *Renew. Sustain. Energy Rev.* **2024**, *195*, 114320. [[CrossRef](#)]
6. Lüth, A.; Seifert, P.E.; Egging-Bratseth, R.; Weibezahn, J. How to connect energy islands: Trade-offs between hydrogen and electricity infrastructure. *Appl. Energy* **2023**, *341*, 121045. [[CrossRef](#)]

7. Zhang, C.; Wei, H.; Zhuang, Y.; Ouyang, Y. Economic evaluation model of offshore wind to hydrogen and its key influence parameters. *Nat. Gas Ind.* **2023**, *43*, 146–154.
8. Lucas, T.R.; Ferreira, A.F.; Pereira, R.B.S.; Alves, M. Hydrogen production from the WindFloat Atlantic offshore wind farm: A techno-economic analysis. *Appl. Energy* **2022**, *310*, 118481. [\[CrossRef\]](#)
9. Abadie, L.M.; Chamorro, J.M. Investment in wind-based hydrogen production under economic and physical uncertainties. *Appl. Energy* **2023**, *337*, 120881. [\[CrossRef\]](#)
10. McDonagh, S.; Ahmed, S.; Desmond, C.; Murphy, J.D. Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment. *Appl. Energy* **2020**, *265*, 114732. [\[CrossRef\]](#)
11. Kim, A.; Kim, H.; Choe, C.; Lim, H. Feasibility of offshore wind turbines for linkage with onshore green hydrogen demands: A comparative economic analysis. *Energy Convers. Manag.* **2023**, *277*, 116662. [\[CrossRef\]](#)
12. Zhang, C.; Song, P.; Hou, J.; Xiao, L.; Wang, X.; Yang, F.; Wang, X. Technical and economic analysis of hydrogen production, storage and transportation by offshore wind power in different scenarios: A Guangdong case study. *Int. J. Hydrogen Energy* **2024**, *94*, 829–837. [\[CrossRef\]](#)
13. Komorowska, A.; Benalcazar, P.; Kamiński, J. Evaluating the competitiveness and uncertainty of offshore wind-to-hydrogen production: A case study of Poland. *Int. J. Hydrogen Energy* **2023**, *48*, 14577–14590. [\[CrossRef\]](#)
14. Pegler, D.L.; Deborah, G.; Robert, R.-S.; Michele, S.; Conley, D.; Benhin, J. Techno-economic analysis for floating offshore wind and offshore green hydrogen. *Int. J. Hydrogen Energy* **2025**, *103*, 538–555. [\[CrossRef\]](#)
15. Dinh, Q.V.; Leahy, P.G. A differential evolution model for optimising the size and cost of electrolyzers coupled with offshore wind farms. *Int. J. Hydrogen Energy* **2025**, *124*, 318–330. [\[CrossRef\]](#)
16. Biggins, F.; Kataria, M.; Roberts, D.; Brown, D.S. Green hydrogen investments: Investigating the option to wait. *Energy* **2022**, *241*, 122842. [\[CrossRef\]](#)
17. Fabianek, P.; Glensk, B.; Madlener, R. A sequential real options analysis for renewable power-to-hydrogen plants for Germany and California. *Renew. Sustain. Energy Rev.* **2024**, *192*, 114159. [\[CrossRef\]](#)
18. Liu, J.; Zhang, Q.; Teng, F.; Wang, L.; Gao, Z.; Wang, G. A new investment decision-making model of hydrogen energy storage technology based on real-time operation optimization and learning effects. *J. Energy Storage* **2024**, *96*, 112745. [\[CrossRef\]](#)
19. Jang, D.; Kim, K.; Kim, K.-H.; Kang, S. Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant. *Energy Convers. Manag.* **2022**, *263*, 115695. [\[CrossRef\]](#)
20. Cheng, C.; Hughes, L. The role for offshore wind power in renewable hydrogen production in Australia. *J. Clean. Prod.* **2023**, *391*, 136223. [\[CrossRef\]](#)
21. Sun, X.; Cheng, X.; Wang, S.; Wang, J.; Zhao, Y.; Zhang, B. Dynamic cost analysis of hydrogen production from wind power and photovoltaic power. *Clean Coal Technol.* **2023**, *29*, 1–10.
22. Hong, F.T.; Lin, H.; Vazquez-Sanchez, H.; Xue, X.; Li, Y.; Zhang, L.; Sarathy, S.M. Minimizing renewable hydrogen costs at producer's terminal gate with alkaline electrolyser, proton exchange membrane, and their co-installment: A regional case study in China. *Int. J. Hydrogen Energy* **2024**, *86*, 1051–1062. [\[CrossRef\]](#)
23. Vidales, A.G.; Semai, M. Platinum nanoparticles supported on nickel-molybdenum-oxide for efficient hydrogen production via acidic water electrolysis. *J. Mol. Struct.* **2023**, *1290*, 135956. [\[CrossRef\]](#)
24. Giampieri, A.; Ling-Chin, J.; Roskilly, A.P. Techno-economic assessment of offshore wind-to-hydrogen scenarios: A UK case study. *Int. J. Hydrogen Energy* **2024**, *52*, 589–617. [\[CrossRef\]](#)
25. Bødal, E.F.; Holm, S.E.; Subramanian, A.; Durakovic, G.; Pinel, D.; Hellemo, L.; Ortiz, M.M.; Knudsen, B.R.; Straus, J. Hydrogen for harvesting the potential of offshore wind: A North Sea case study. *Appl. Energy* **2024**, *357*, 122484. [\[CrossRef\]](#)
26. Lin, H.Y.; Liao, C.P. Optimization deployment and evaluation of demand-driven offshore wind power electrolysis hydrogen supply chain. *Int. J. Hydrogen Energy* **2025**, *149*, 149870. [\[CrossRef\]](#)
27. Zou, P.; Lin, H.J.; Zhou, X.J.; Zou, Y.L.; Li, Y.Y.; Yan, G.H.; Duan, X.; Cai, J. Control strategies for multi-electrolyzer alkaline hydrogen generation systems improving renewable energy utilization and electrolyzer lifespan. *Renew. Energy* **2025**, *253*, 123628. [\[CrossRef\]](#)
28. Wang, J.; Yang, J.; Feng, Y.; Hua, J.; Chen, Z.; Liao, M.; Zhang, J.; Qin, J. Comparative experimental study of alkaline and proton exchange membrane water electrolysis for green hydrogen production. *Appl. Energy* **2025**, *379*, 124936. [\[CrossRef\]](#)
29. Longstaff, F.A.; Schwartz, E.S. Valuing American Options by Simulation: A Simple Least-Squares Approach. *Rev. Financ. Stud.* **2001**, *14*, 113–147. [\[CrossRef\]](#)
30. Zhang, M.; Tang, Y.; Liu, L.; Zhou, D. Optimal investment portfolio strategies for power enterprises under multi-policy scenarios of renewable energy. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111879. [\[CrossRef\]](#)
31. Virah-Sawmy, D.; Beck, F.J.; Sturmberg, B. Ignore variability, overestimate hydrogen production—Quantifying the effects of electrolyzer efficiency curves on hydrogen production from renewable energy sources. *Int. J. Hydrogen Energy* **2024**, *72*, 49–59. [\[CrossRef\]](#)

32. Liang, T.; Chai, L.; Cao, X.; Tan, J.; Jing, Y.; Lv, L. Research on Energy Storage Scale Optimization Method for Off Grid New Energy Hydrogen Production Systems. *J. Chin. Soc. Power Eng.* **2025**, *45*, 452–463.
33. China Energy Engineering Group Co., Ltd. Public Display of Successful Bidders for the 2024 Centralized Procurement Project of Hydrogen Production Equipment by China Energy Engineering Group Co., Ltd. 2024. Available online: <https://ec.ceec.net.cn/> (accessed on 20 February 2025).
34. Liu, D.; Li, J.; Qi, Y.; Guo, Y.; Bao, M. Wind Farm Energy Storage Optimization Configuration Considering Carbon Benefit and Operation Strategy. *Acta Energiæ Solaris Sin.* **2025**, *46*, 664–675.
35. National Energy Administration. 2023 National Monitoring Report on Renewable Energy Power Development. 2024. Available online: https://zfxgk.nea.gov.cn/2024-10/10/c_1310787115.htm (accessed on 30 June 2025).
36. Clean Development Mechanism. Large-Scale Methodology: Hydrogen Production from Electrolysis of Water. 2024. Available online: <https://cdm.unfccc.int/methodologies/DB/X31VJK28R9DCAKOMET9BRS2PXSIKKX> (accessed on 19 March 2026).
37. International Renewable Energy Agency. *Renewable Power Generation Costs in 2022*; International Renewable Energy Agency: Abu Dhabi, Saudi Arabia, 2023.
38. Wiser, R.; Rand, J.; Seel, J.; Beiter, P.; Baker, E.; Lantz, E.; Gilman, P. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nat. Energy* **2021**, *6*, 555–565. [CrossRef]
39. Shanghai Environment and Energy Exchange. Price Information of China's Hydrogen Price Index System. 2024. Available online: <https://www.cneex.com/c/2024-12-16/495871.shtml> (accessed on 2 April 2025).
40. Research Center of Sustainable Development of Fudan University. Fudan Carbon Price Index. Available online: <https://rcsd.fudan.edu.cn/info/1114/1887.htm> (accessed on 10 September 2025).
41. Kumar, P.; Date, A.; Shabani, B. Techno-economic analysis of an integrated desalination-renewable-hydrogen system for zero-emission freshwater and electricity production. *Energy Convers. Manag.* **2026**, *353*, 121231. [CrossRef]
42. Traisak, O.; Kumar, P.; Das, R.K.; Vahaji, S.; Zhang, Y.; Velankar, V.; Date, A. Integrated Thermoelectric Power Generation and Membrane-Based Water Desalination Using Low-Grade Thermal Energy. *Energies* **2026**, *19*, 1054. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.