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ARTICLE

Assist in GHG Abatement of Offshore Ships: Design and Economic Analysis of an Integrated Utilization Model of Hydrogen-powered Ship and Offshore Wind Power

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ABSTRACT

As a hopeful solution to help the shipping sector achieve the greenhouse gas (GHG) abatement goal of the IMO by 2050, the application of hydrogen-powered ships has attracted more and more attention. To solve the problem of hydrogen supplement for offshore polymer electrolyte membrane fuel cell (PEMFC) ships, this paper presents a scenario design for the integrated application of coastal hydrogen-powered ships and offshore wind power, and analyzes its techno-economic feasibility. This model concept considers the problems in offshore hydrogen transportation and offshore wind power development together. It provides a feasible integrated scheme and operation mode for the combination of offshore wind power and hydrogen energy storage. A transformation scheme is also provided for the marine ranch ships, and these PEMFC-powered ships are combined with the hydrogen production of offshore wind farms. The analysis results show that the integrated utilization model is economically feasible and with a significant effect on decarbonization. It also shows great potential for further expansion to other coastal areas.

1. Introduction

To achieve carbon neutrality in the future, carbon emissions need to be controlled from the energy consumption side and energy production side respectively. On the side of energy consumption, the main consideration are industrial power and transport carbon reduction. There is already a good measure to reduce carbon in land transport, namely electrification [1], when traditional battery energy storage cannot meet the demand alone, polymer electrolyte membrane fuel cells (PEMFCs) power can be coupled with it to achieve a longer endurance and faster energy replenishment speed. Before being applied to civil ships, the more mature power application of fuel cells (FCs) in

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ships is PEMFC in the HDW submarines working as air independent propulsion (AIP) [2]. This type of submarine has been in service since the 1990s. In the civil market, Golden Gate Zero Emission Marine, an American company, built the first hydrogen fuel cell ship in 2018. It's called Water Go Round, with a maximum speed of 22 knots and 84 passengers. The low density of hydrogen and the PEMFC's proneness of remarkable degradation restrict the application of PEMFC in surface ships. When it is used on ships, the hydrogen-fueled PEMFC is usually hybridized with a battery energy storage system [3]. PEMFC and lithium-ion batteries both have the problem of remarkable degradation which raises the need for an energy management strategy [4]. According to the research of Chiara Dall' Armi et al., with an appropriate energy management strategy, the overall lifetime of the plant can be increased more than twice [5]. With the ageing of components, the decrease in PEMFC efficiency leads to an increase in hydrogen consumption [6]. This cause the need for additional space for the hydrogen storage system to ensure the normal operation of the ship after a period of service. The lifetime and hydrogen storage problems faced by PEMFC ships will be gradually solved in the process of PEMFC transportation industry development. In contrast, the scheme proposed in this paper focuses more on the hydrogen refuelling of PEMFC ships. For carbon reduction in offshore transportation, offshore fishing boats and small sightseeing boats are suitable to use PEMFC to achieve zero carbon emission, with appropriate control and optimization strategies, and energy storage systems [7]. However, it is difficult to refuel hydrogen when it is sailing on the sea, and frequent landing for hydrogen charging would bring a lot of inconvenience to its normal operation. It is also important to note that, if blue hydrogen is used, its life-cycle greenhouse gas emission intensity is still higher than that of LNG and diesel [8,9], because of the large amount of CO_2 emissions during the hydrogen generation process of the SMR and the electricity consumed in the hydrogen compression process [10]. Green hydrogen must be used if hydrogen-powered maritime transport is to achieve a full life-cycle of zero carbon [11], but it accounts for only 1% of the domestic hydrogen production in China. This problem brings our focus to a wide range of renewable sources of energy, also located offshore.

In the process of renewable energy development, wind energy is favored by many countries in the world because of its short construction cycle, low environmental requirements, rich reserves and high utilization ratio. Offshore wind power also has advantages such as non land occupation and being close to the load center area with high power demand [12]. The power of wind power depends on the natural wind and is affected by many natural factors. Its fluctuation and irregularity make it difficult to be fully integrated into the grid even if it is coordinated with other power sources for peak shaving [13]. Under such circumstances, this extra part of wind power is forced to be abandoned [14]. Storing and distributing hard-to-use wind power can effectively improve the utilization rate of wind power, but traditional electromagnetic energy storage methods cannot meet the demand for wind energy storage [15], and it's difficult to use those traditional storage systems in the marine environment. Under these circumstances, hydrogen energy storage systems appear as an alternative to conventional storage technologies [16]. The green hydrogen produced by wind power can be used for PEMFC-powered transportation to achieve zero carbon emissions for the whole life cycle and help increase the efficiency of renewable energy use and their share in the energy mix [17,18]. With the wind-hydrogen energy storage system, massive wind energy curtailment can be converted into commercial profits [19,20]. It can even build a dedicated wind farm for hydrogen production, some researchers have demonstrated the feasibility of this model [21]. But compared to conventional liquid fuels, hydrogen has a low volumetric energy density, which brings problems to its storage and transport. This problem is also reflected in hydrogen production from wind power fields in previous industrial projects [22-24]. The NORTH2 project in the Netherlands uses large offshore hydrogen plants to deliver wind power [25]. AquaPrimus is the first sub-project of the German AQUAVENTUS project, and it plans to 2028 a hydrogen plant on the base of a wind turbine to deliver green hydrogen to the region through specially laid pipelines. Poshydon of the Netherlands, the world's first offshore wind-hydrogen project, will use a natural gas pipeline to mix hydrogen and natural gas into its national gas pipeline network [26,27].

Most of the existing plans for offshore hydrogen production worldwide are designed to take into account the demand for hydrogen on land, and the annual output often reaches 10,000 tons or even 100,000 tons, so they can only consider the way of sending wind power to shore or offshore platform to make hydrogen by pipeline to shore, not considering the possibility of hydrogen storage and consumption offshore. There have also been examples of combining hydrogen generation from wind power with characteristic transportation demand, but these attempts are also applicable to the land transportation field [28,29], in order to supply hydrogen produced by wind power for PEMFC vehicles [30]. Using green fuels like these green hydrogen to replace traditional fossil fuels is an effective way for the maritime sector to reduce carbon emissions [31]. If each of the scattered offshore hydrogen platforms in the offshore hydrogen project is used to supply a group of coastal PEMFC ships with relatively fixed but not massive hydrogen, then there is no need to consider the transport of hydrogen. Marine ranch is well suited for this, with a fixed number of ships and a fixed working trajectory. Therefore, offshore hydrogen production platforms and offshore hydrogen refuelling stations can be considered at locations close to both marine ranch and wind farms, allowing PEMFC-powered ships to refuel hydrogen on their daily route. The energy consumption of the marine ranch ships is relatively fixed every day, and the offshore hydrogen production platform can be produced on demand according to the surrounding conditions, which can reduce the cost of the hydrogen storage process and unnecessary energy loss, and avoid the hydrogen storage and consumption problems that offshore hydrogen station faced before. The main challenge of applying green hydrogen to ships is the storage of H_2 on ships [31], however, in this mode, PEMFC ships can timely replenish hydrogen near the work area, which to some extent alleviates the problem of hydrogen storage. In the future, it can also cooperate with the composite hydrogen storage technology with higher capacity, lower weight, and improved safety [32] to further solve the problem of hydrogen storage on ships. Based on it, this paper presents a scenario design for the integrated application of coastal PEMFC ships and offshore hydrogen stations by wind power. It aims to solve the hydrogen refuelling problem of offshore PEMFC ships and provide a feasible integrated scheme and operation mode for the combination of offshore wind power and hydrogen energy storage. The analysis of the daily operation of offshore hydrogen stations and marine ranch PEMFC ships shows that this model is economically feasible. It also shows great potential for further expansion to other coastal areas.

2. Model Description

This model uses a grid-connected way of hydrogen production from wind power, because it can obtain power from the power grid to maintain the normal operation of the alkaline electrolytic cell when the output power of wind turbines cannot meet the requirements. If the system only relies on wind power without coordinating the power grid, it may cause damage to the electrolytic cell when the fluctuation is large. The offshore hydrogen production and refuelling station can be built on the original offshore platform of the wind farm. It uses alkaline electrolytic cells to produce hydrogen. Although using proton exchange membrane water electrolysis (PEMWE) can obtain lower energy consumption and higher hydrogen purity, it brings higher costs and requires more frequent maintenance which makes it less suitable for this scenario than alkaline electrolytic cells.

In this scenario design, the quantity, types and performance parameter data of the ships in designated marine ranch were taken into consideration to specify the corresponding transformation scheme, and shows the theoretical hydrogen consumption data. The output of offshore hydrogen stations is set based on the daily hydrogen demand of these ships, and the redundancy is reserved to cope with different conditions. The wind power output allocated for offshore hydrogen stations is set based on the power consumption of developed alkaline electrolytic cells, hydrogen purification/compression devices and other equipment. The power consumption of the whole hydrogen production process is set as 5.156 kWh/Nm^3. In the actual operation, the dispatching control system needs to adjust the power according to the available idle wind power data to meet the requirements of the power grid and all hydrogen production equipment at the same time. However, the main starting point of this model is to provide the nearby hydrogen supply for the application of PEMFC on offshore vessels. Therefore, this paper sets the power supply and hydrogen output of offshore wind stations as a constant mean. The calculation part of this paper is focused on the cost recovery period, net profit and emission reduction. In the calculation process, it uses the ideal state with additional redundancy upper limit to approximately replace the fluctuations caused by various practical factors. The energy flow path of this scenario designed is shown in Figure 1.

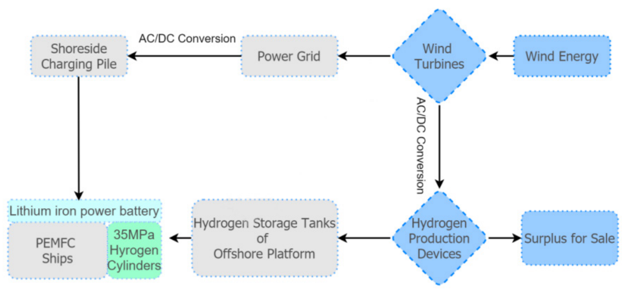

Figure 1. The flow path of energy in this scenario.

A wind farm project in the Yellow Sea in northeast China, covering an area of about 48 square kilometers, is the background of the initial scenario design for the demonstration of PEMFC ships and offshore hydrogen stations. The center of the site is located about 19.1 km from the coast. There are 60 wind turbines with a total installed capacity of 300 MW.

In this initial scenario of integrated utilization, offshore wind farm investors will invest in a 1,000 kg per day offshore hydrogen production and refuelling station on an offshore platform about 15 kilometers offshore, and the H_2 is sold to hydrogen-powered breeding boats and sightseeing boats of a nearby marine ranch. Investors of the marine ranch invest in hybrid PEMFC boats with hydrogen fuel cells and power batteries that use hydrogen from offshore wind farms to replace conventional diesel fuel. On the one hand, it can save some fuel costs under the current subsidy policy, on the other hand, it can avoid the emission of diesel engines, and improve the efficiency of energy conversion, so as to achieve the effect of energy saving and emission reduction.

The investors of the marine ranch have invested about 1.44 million \$ to build an offshore leisure platform in the marine ranch, which will integrate offshore fishing and offshore sightseeing, and make it a comprehensive platform that takes into account both tourism and aquaculture operations. As shown in Figure 2, the ranch boats and tourist boats use the power provided by the battery system to drive to the offshore hydrogen station of the wind farm for refuelling in the morning and then the boats can go to the working area, sightseeing boats are responsible for transporting tourists to and from tourist attractions and the shore. All of the ships return to offshore hydrogen stations before running out of fuel, return to shore at the end of the day and recharge at night through shore-based charging posts.

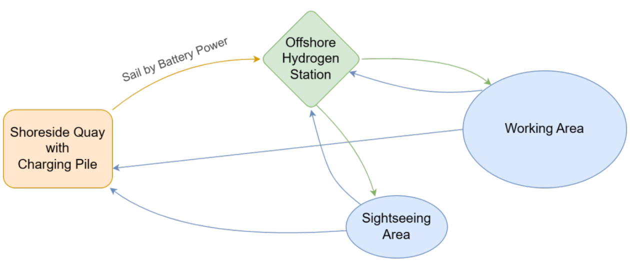

Figure 2. Daily route of marine ranch ships in this scenario.

3. Results

3.1 Composition and Analysis of Investment Cost

Initial Investment Estimate of Offshore Hydrogen Plant

The hydrogen station needs about 58000 kWh to produce 1000 kg of hydrogen per day. To meet this production capacity, the hydrogen station needs to be equipped with a 2.5 MW electrolytic hydrogen production system. (The energy conversion efficiency of the entire system is recorded as 55%). The cost of hydrogen production in offshore wind farms is mainly composed of the cost of the offshore converter station, the hydrogen production system, the hydrogen compressor, the hydrogen cylinders, the hydrogen charging system and the installation costs, as shown in Table 1. The hydrogen production system consists of a seawater desalination unit and an electrolytic water hydrogen production unit, the hydrogen charging system includes the charge machine, the hydrogen pipeline system, the dispersing system, the displacement purging system, the instrument air system, the safety monitoring system and other pipeline materials for connection. The hydrogen compressor requires two diaphragm compressors with a rated exhaust pressure of 45 MPa and a hydrogen compression rate of 500 kg per day. The hydrogen cylinder adopts a 45 MPa hydrogen cylinders group, and the hydrogen charging system needs four 35 MPa charging machines. The installation cost is estimated according to 10% of the total cost, and the initial investment of the offshore hydrogenation station is about 3.469 million \$, expressed in C_{CF}.

Table 1. Cost estimates for offshore hydrogen stations.

Equipment	Unit price (million \$)	Total cost (million \$)
Offshore converter station	0.287/MW	0.718
Hydrogen production system	0.287/MW	0.718
Hydrogen compressor	0.431	0.862
Cylinders and refueling systems	0.825	0.825
Installation costs	0.346	0.346
Total cost		3.469

Initial Investment Estimates for Marine Ranch

After conducting research on marine ranches that integrate aquaculture and tourism, such as the Genghai No.1, the small breeding boats and sightseeing boats that are commonly used are selected as the expected renovation targets. The basic parameters of 30 working boats and 15 sightseeing boats for the marine ranch are shown in Table 2.

Table 2. Basic parameters of marine ranch boats.

Parameter	Breeding boat	Sightseeing boat
Speed (knots)	9	10
Length (m)	10	13.5
Ship width (m)	2.85	3.5
Draft (rice)	0.59	0.73
Engine power (kW)	16	60
Daily working hours (h)	10	10

As shown in Table 3, the fuel cell system power of the breeding boat is 20 kW, which considers both power generation and bucking-wave performance. With a power cell capacity of 40 kWh, it can run at 9 knots while operating at 80% performance output. The fuel cell system power of the sightseeing boat is 75 kW, with a power cell capacity of 150 kWh. The design principle is that it can be used as a separate energy source for ships to operate at rated power for more than 2 h, and can supplement the power needed for bucking-wave navigation, and be used as backup power for electric valves and other equipment. A 35 MPa gas cylinder has an H_2 storage density of 20-22 g/L and a hydrogen storage capacity of about 3 kg. The endurance is calculated according to the working condition of these ships at rated power, and it requires that ships operate at rated power and run for more than 5 hours.

Table 3. PEMFC ship modification plan for marine ranch.

	Breeding boat	Sightseeing boat
Power of fuel cell system (kW)	20	75
Power cell capacity (kWh)	40	150
Rated power (kW)	16	60
Bottle pressure (MPa)	35	35
Volume of carbon fiber bottle (L)	140	140
Number of carbon fiber bottles	2	8
Hydrogen storage (kg)	6	24
Sailing duration (h)	5.6	6
Number of vessels	30	15

As shown in Table 4, the modification costs of hydrogen-powered boats include the cost of fuel cell power generation system, hydrogen storage system, power cell system, accessory cost and other costs. Accessories mainly include electric propulsion systems, power grids and power control systems. Other costs consist of labor costs and hull modification costs. The cost of a fuel cell system is about 718 $/kW, the cost of a power cell is about 215.5 $/kWh, the hydrogen storage capacity of 35 MPa hydrogen cylinder is about 3 kg, and the cost of a single cylinder is about 2155$, the initial investment for the marine ranch boats transformation is about 3.32 million $.

Table 4. Cost estimation of marine ranch PEMFC ship modification.

Part of the cost	Cost of breeding boat ($)	Cost of sightseeing boat ($)
Fuel cell system	14,368	53,880
Power battery system	8,620	32,328
Hydrogen storage system	4,310	17,241
Cost of accessories	7,184	28,736
Other costs	2,874	14,368
Cost of upgrading a single ship	37,356	146,553

It costs 58200$ to build thirty 7 kW charging posts at 144$ and fifteen 120 kW charging posts at 3592$, as shown in Table 5, the initial investment cost of the marine ranch investor is about 4.815 million $, expressed in C_{CR} including 3.32 million $ to retrofit a hydrogen-powered ship, 58200$ for charging posts and 1.437 million $ for a marine sightseeing-entertainment platform.

Table 5. Cost estimation of shore charging posts.

	Unit price ($)	Total cost ($)
7 kW charging post	144	4,320
120 kW charging post	3,592	53,880
Total cost of charging posts		58,200

3.2 Cost Recovery Period Analysis

Cost Recovery Period Analysis of Offshore Wind Farm Investors

According to the above data, the initial investment cost of offshore hydrogen station (C_{CF}) is 3.469 million $. About 1,000 kg of hydrogen produced per day are sold to the marine ranch at 2.87$ per kilogram. Calculated by 300 days per year (matching the business hours of the marine ranch), the annual income can reach 0.862 million $. An annual investment of 0.534 million $ will be required, including annual maintenance costs (34483$ at 1 percent of the cost of the equipment) and electricity consumption costs (0.5 million $ for 58,000 kWh electricity per day at 0.0287$ per kWh). Therefore, the annual net income can reach 0.328 million $, expressed in C_{IF}. According to Initial investment/annual net income = years of cost recovery, described by Equation (1).

$$T_F=C_{CF}/C_{IF} \tag{1}$$

The years of cost recovery for wind farms without subsidies can be calculated. In Dalian, a one-off subsidy of up to 0.862 million $ (expressed in C_{SF}) will be given to new hydrogen refueling stations put into use after 2023, not exceeding 30 percent of the investment. According to Initial investment subtract subsidies/annual net income = years of cost recovery with subsidies, described by Equation (2).

$$T_{SF}=(C_{CF}-C_{SF})/C_{IF} \tag{2}$$

The years of cost recovery for wind farms with subsidies can be calculated, as shown in Table 6.

Wind farm investors can earn a profit of 0.328 million $ a year from the sale of hydrogen. Without taking into account subsidies, investors can recover the cost of their initial investment in 10.59 years, if the government subsidies for the construction of hydrogen stations (onshore) are taken into account, the investment cost recovery period will be shortened to 7.96 years, and the government subsidies can bring the cost recovery period forward to about 2.63 years, if the government in the follow-up to the construction of offshore hydrogen station subsidies.

Table 6. Cost recovery years for offshore wind farm investors.

Component	Amount (million $)
Initial investment	3.467
Annual income	0.862
Annual expenses	0.534
Annual net income	0.328
Cost recovery period	10.59
Cost recovery period (subsidy)	7.96

Analysis of Cost Recovery Period of the Marine Ranch Investor

Based on the above data, it can be calculated that the cost of rebuilding the ship is 3.319 million $, the cost of shore charging posts is 58200$, the cost of building an offshore integrated entertainment platform is 1.437 million $, and the initial investment of marine ranch is 4.81 million $, expressed in C_{CR}. It also needs to invest 0.287 million $ a year in the operation and maintenance of the hydrogen-powered ships, taking the fuel cost savings compared with traditional diesel ships and the entrance fees of the offshore integrated platform as income. Then the annual net income of marine ranch investors' hydrogen investment can reach 0.552 million $, expressed in C_{IR}. Taking into account Dalian's subsidies at 0.498 million $ (expressed in C_{SR}), for 15% of the total 2023 cost of hydrogen-powered ships purchased and put into operation in 2023, according to Initial investment/annual net income = years of cost recovery, described by Equations (3) and (4).

$$TR = C_{CR}/C_{IR} \tag{3}$$

$$TSR = (C_{CR} - C_{SR})/C_{IR} \tag{4}$$

We can calculate the years of cost recovery with and without subsidies for marine ranch investors, as shown in Table 7.

Table 7. Marine ranch investors' cost recovery years.

Component	Amount (million $)
Initial investment	4.81
Annual income	0.839
Annual expenses	0.287
Annual net income	0.552
Cost recovery period	8.73
Cost recovery period (subsidy)	7.82

The total diesel consumption of 30 marine ranch breeding boats with the same performance parameters is about 1320 liters per day, and that of 15 sightseeing boats with the same performance parameters is about 2460 liters per day, which is a total of 3780 liters, the price of diesel is calculated at 1.12$ per liter and the annual working days are calculated at 300 days. The annual fuel cost of marine ranch ships is about 1.266 million $, and the annual fuel cost of the hydrogen-powered ships is 0.862 million $, which can save 0.404 million $ per year. The price of the ticket for the marine entertainment platform is set at 12.79$ per person, calculated on the basis of 40,000 tourists per year, with an annual income of 0.511 million $.

The annual net income of marine ranch can reach 0.552 million $. Without taking into account subsidies, marine ranch investors can recover the cost of their initial investment after 8.73 years, if the government subsidy for the hydrogen station is taken into account, this marine ranch can complete the cost recovery of the initial investment after 7.82 years. The government subsidy can bring the cost recovery period forward by about one year.

3.3 Cost Recovery Period Analysis Considering Other Influencing Factors

In the last part of the cost-recovery cycle, we only assumed that the offshore hydrogen station is matched with the operation of the marine ranch and only produces hydrogen 300 days a year. But if the plant is operating year-round, selling excess hydrogen to other users for revenue, the cost-recovery cycle could be further shortened to 6.54 years, as shown in Figure 3. The sightseeing revenue of the marine ranch before was assumed to be constant every year, but this new model of tourism has the potential for continuous development and expansion. If tourism profits increase by 5% every year, the cost-recovery cycle could be shortened to about seven years, and total profits over the first 20 years would be about 65 percent higher. (This growth model becomes less credible as the period grows). In this scenario designed, the offshore hydrogen station is currently matched with the operating time of the marine ranch. However, if it operates year-round and sells excess hydrogen to other users, it will gain higher profits, as shown in Figure 4.

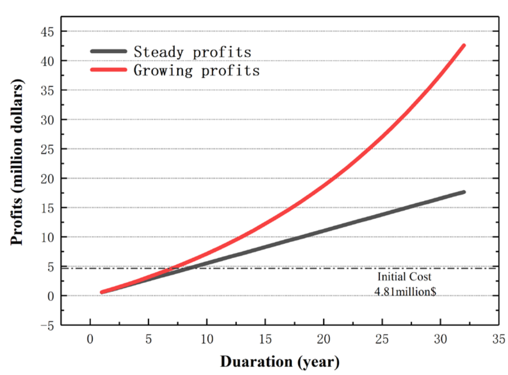

Figure 3. Total net income from marine ranch sightseeing.

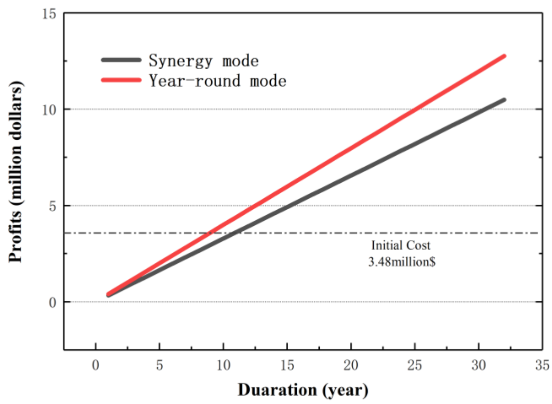

Figure 4. Total net revenue of offshore hydrogen stations.

In this scenario, factors such as changes in hydrogen price, changes in the technological maturity of PEMFC system, and the level of equipment maintenance and management will all have impacts on the cost recovery period. Therefore, further sensitivity analysis is needed. The impact of changes in the above factors on the results is shown in Figures 5, 6, 7, and 8.

In fact, the growth level of marine ranch tourism income will be affected by multiple factors and present uncertainty. The change in hydrogen price is the most intuitive factor affecting the operating profit of PEMFC ship users. When the average price of hydrogen gas is different, the change curve of the cost recovery period for investors of PEMFC ships is shown in Figure 5, and its impact on the cost recovery period of the hydrogen station is shown in Figure 6. (The upper price limit of 20 RMB for H_2 sold by hydrogen station is stipulated by preferential policies). From them, it can be seen that hydrogen prices within the range of 2.65 \$/kWh to 2.88 \$/kWh are more suitable for both parties, which can control the cost recovery period of both parties within 10 years. In addition, the current policy subsidies have a more significant helping effect on the offshore hydrogen station.

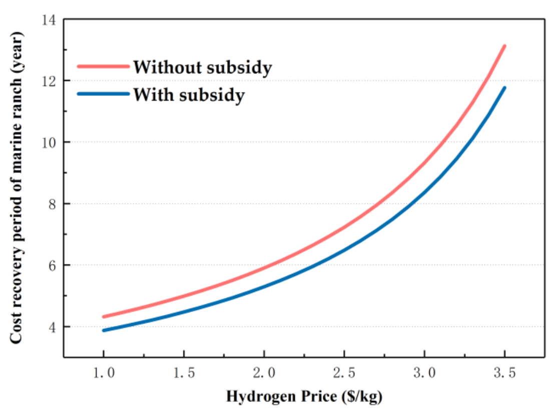

Figure 5. The cost recovery period of marine ranch is affected by H_2 price.

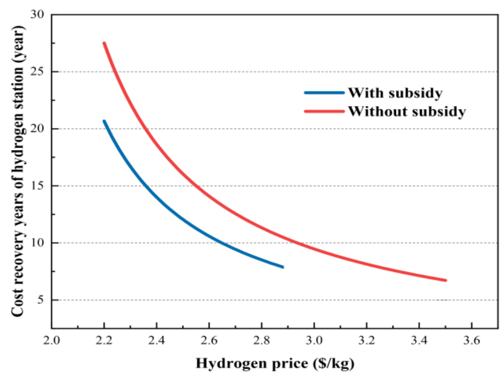

Figure 6. The cost recovery period of the H_2 station is affected by the H_2 price.

The initial construction cost of offshore hydrogen refuelling stations will decrease with the development of the technological maturity of electrolytic hydrogen production. In this scenario, when the expected cost recovery period remains unchanged, the hydrogen price of the hydrogen station is mainly affected by the initial construction cost of the hydrogen refuelling station. When the cost recovery period of a hydrogen station is 8 years (subsidies were taken into consideration), the trend of hydrogen price is shown in Figure 7.

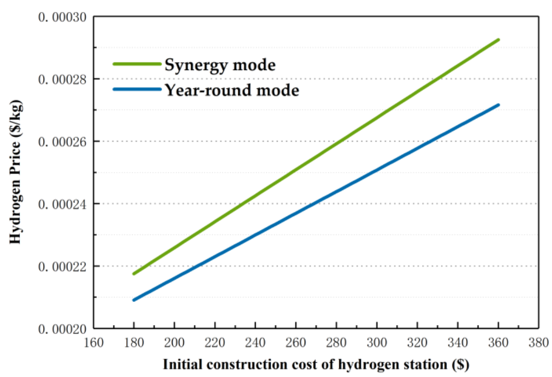

Figure 7. Hydrogen price trend of the offshore hydrogen station.

In the future, with the development of this industry, it is foreseeable that the price of hydrogen and hydrogen stations will decrease, which can effectively improve the application economy of PEMFC ships.

Changes in equipment maintenance expenses can also have an impact on the results. Due to differences in maintenance and management capabilities, when the maintenance cost of equipment fluctuates within 0.4 to 2.2 times the original value, its impact on the cost recovery period is shown in Figure 8. It can be seen that the fluctuation of maintenance expenses has a very limited impact on the offshore hydrogen station, but it is a very important issue for marine ranch investors.

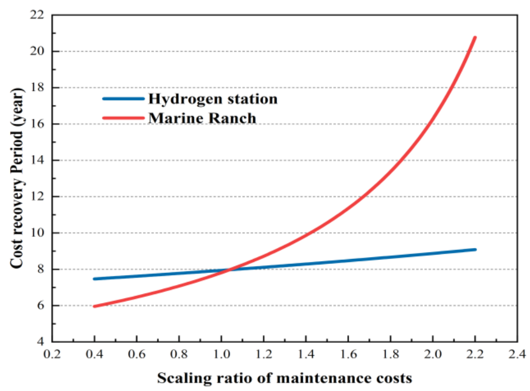

Figure 8. The impact of changes in maintenance expenses on the cost recovery period.

3.4 Promotion Scenario of the Integrated Utilization Operation Mode

In the scenario design of the integrated utilization operation mode of the hydrogen-powered ship, the size of the offshore hydrogen production and refuelling unit is relatively small, the industrial technology of each component is relatively mature, and the retrofit scheme of the hydrogen-powered ship is relatively perfect, it is suitable for further promotion as elements of a larger scale distributed design in the development and construction planning of offshore wind power and hydrogen-powered ships. In the further scenario design, four adjacent wind farm sites offshore of Liaoning province can be selected, and a hydrogen production and refuelling station with a daily hydrogen production of 1 t can be built on the platforms in their respective areas close to the offshore fishing operation area, it serves as a source of hydrogen for nearby hydrogen fuel cell powered farming breeding boats and sightseeing ships, and, as the total hydrogen supply in the area increases, it can provide enough hydrogen for more hydrogen-powered ships. Larger fishing ships such as hydrogen-powered trawlers and shrimp trawlers could also be considered. Because such ships require larger power-cell capacity, the investors would need to install 120 kW charging posts. The parameters and cost are shown in Tables 8 and 9.

Based on the above data, it can be calculated that the initial investment cost is 29.667 million $ and the annual investment is 2.283 million $, which includes annual maintenance costs (0.287 million $ per year, estimated at 1 percent of the equipment cost) and electricity consumption costs (0.0287 $/kWh, 231,500 kWh per day, 1.996 million $ per year), On the other hand, the 100 diesel vessels with the same parameters will consume about 13,025 liters of diesel per day. Based on their working duration of 300 days per year, the annual fuel cost for these ships will be about 4.362 million $. From this, we can calculate the change curve for the cost of PEMFC ships and diesel-powered ships as shown in Figure 9.

Table 8. PEMFC ship modification plan for marine ranch.

Component	Fishing trawler	Shrimp trawler
Speed (knots)	10	10
Length (m)	39	35
Power of fuel cell system (kW)	300	200
Power cell capacity (kWh)	600	450
Rated power (kW)	240	160
Bottle pressure (MPa)	35	35
Volume of hydrogen cylinder (L)	320	320
Number of hydrogen cylinder (L)	14	10
Hydrogen weight (kg)	91	65
Sailing duration (h)	5.7	6.1

Table 9. Cost of marine ranch PEMFC ship modification.

Costs component (million $)	Fishing trawler	Shrimp trawler
Fuel cell system	0.216	0.143
Power battery system	0.129	0.097
Hydrogen storage system	0.050	0.036
Cost of accessories	0.287	0.216
Other costs	0.029	0.021
Cost of upgrading a single ship	0.711	0.513

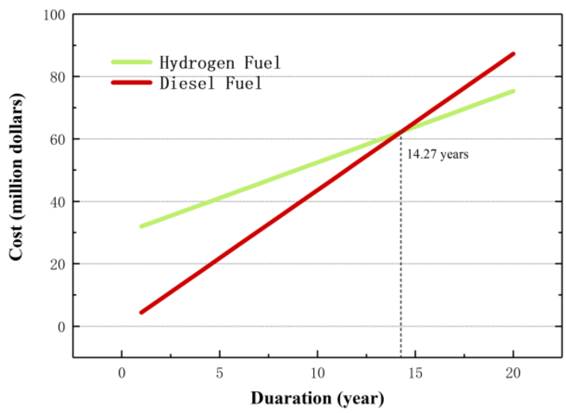

Figure 9. Cost of PEMFC ships and diesel ships.

As can be seen from this chart, the total cost of using hydrogen from offshore wind power as fuel is mainly concentrated on the initial cost, and the initial cost is very high. However, in terms of operating and maintenance costs, using hydrogen from offshore wind power as fuel has a big advantage over traditional diesel fuel. The total cost after the 15th year already has an advantage over traditional diesel fuel, and the longer it takes, the greater the advantage is.

A liter less diesel is equivalent to a 2.63 kg reduction in CO_2 emissions. This expansion would reduce CO_2 emissions by around 10,000 tonnes and sulphur dioxide emissions by 3358.4 kg per year (calculated as 0.005% sulfur content of diesel fuel).

4. Discussion

In this promotion scenario, additional passing hydrogen-powered ships could be added to it to increase demand for hydrogen, especially during the fishing off-season. This will not only make full use of the output capacity of offshore hydrogen stations to shorten the payback period for offshore wind power investors, but also create conditions for the use of more hydrogen-powered ships, and reduce fuel costs for ship owners. Furthermore, with good offshore wind power infrastructure, there are many offshore wind farms located within 100 km of each other in China, especially in the eastern and southern parts, if these wind farm investors build a chain of offshore hydrogen production and refuelling stations at reasonable intervals, they will be able to provide seamless hydrogen supply for the ships sailing along the coast, to promote the full use of renewable energy and hybrid PEMFC ships industry development. Furthermore, it should be noted that this proposed model requires nearby offshore wind farms in the sea area and the conditions to allow ships to berth and refuel. In addition, if the infrastructure construction of other alternative fuels along the coast is also relatively complete, the competitiveness of the proposed model will also be weakened.

5. Conclusions

In this paper, a demonstration scenario for the integrated utilization of offshore PEMFC ships and offshore wind power is presented, and the technical and economic analysis of this operation mode is made. It was also compared with traditional fuel ships. The following conclusions are drawn.

In this integrated application scenario, an offshore wind investor would ideally be able to recoup their investment costs in just 6.54 years and earn 0.399 million $ thereafter. Marine ranch investors can recover their costs in six to eight years, depending on the development of the sightseeing market and government subsidies for PEMFC-powered transportation.

Factors such as H_2 prices, policy subsidies, and maintenance expenses all have varying degrees of impact on the results. The price of hydrogen is the most significant factor. Among other factors, the impact of policy subsidies is more evident for the offshore hydrogen station, while for investors of the marine ranch, maintenance expense is a more significant issue.

The promotion scenario can reduce CO_2 emissions by around 10,000 tons per year, and SO_2 emissions by 3,358.4 kg per year, and the overall cost of using hydrogen as a fuel is lower than conventional diesel fuel starting in the 15th year. However, the initial investment cost of fuel cell ships is high, and its economic benefits need to rely on policy incentives to further improve.

Author Contributions

Conceptualization, G.Y.; Methodology, G.Y. and H.W.; Software, X.L.; Validation, X.L. and B.S.; Formal analysis, X.L. and B.S.; Resources, G.Y. and H.W.; Writing—original draft preparation, X.L.; Writing—reviewing and editing, G.Y., H.W. and X.L.; Supervision, G.Y. and H.W.; Project administration, G.Y.; Funding acquisition, G.Y.

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Conflict of Interest

The authors declare no conflicts of interest.

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