



# Design of Charging Station System for Underwater High Energy Density Oxyhydrogen Fuel Cell

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**Abstract.** Based on the physical structure of the 20-foot container, this paper carries out the theoretical analysis of underwater charging station system about energy allocation of oxyhydrogen fuel cell and lithium batteries, and carries out the analysis of the equipment and components that have a great impact on the total weight of the charging station system, and summarizes the design principles to improve the energy density of the charging station system. The energy density of the underwater charging station is comprehensively improved in the aspects of technical design, material selection, structure and technology. The maximum structural configuration of hydrogen and oxygen gas storage vessel is carried out. The oxyhydrogen fuel cell and its auxiliary system realize the compact and lightweight design. The standard pressure chamber also achieves a lightweight design under the condition of 300m underwater pressure operation. The design and calculation results show that the charging station has high energy density, simple engineering implementation and can meet the requirements of underwater closed environment operation.

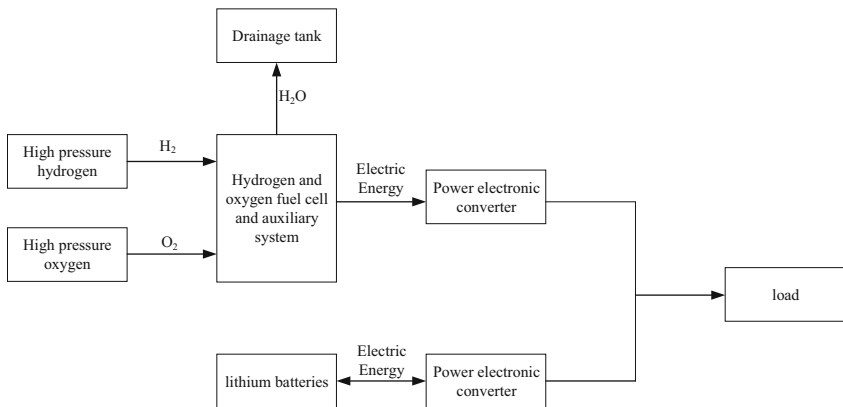
**Keywords:** Underwater power station · Oxyhydrogen fuel cell system · High energy density · Lightweight design

## 1 Introduction

For the long-term and small-volume requirements of power equipment, it is generally difficult to meet the system operation requirements by relying solely on high energy density batteries. In addition, considering that marine temperature is low, the discharge performance of the traditional battery is attenuated, and battery energy cannot meet the needs of more scenarios. The fuel cell is a representative energy with high energy density, which has the advantages of high energy conversion efficiency, low vibration noise, no exhaust emissions, and flexible module combination. The oxyhydrogen fuel cell is an energy conversion device that converts the chemical energy of hydrogen and oxygen into electrical energy through the electrode reaction, and its reaction process does not involve combustion, thus breaking the limit of power generation in a low temperature environment [1], which can be used for the development of underwater long range, large

navigation depth and high stealth closed cycle unmanned underwater charging station [2].

The power dynamic characteristics of oxyhydrogen fuel cells are soft, and the dynamic response speed is slow. The idea of adding lithium batteries to work with oxyhydrogen fuel cells is adopted, and the dynamic response of lithium batteries is fast to support the bidirectional charging and discharging characteristics. This paper designs an underwater high energy density fuel cell charging station system with hydrogen and oxygen as the main energy source, as shown in Fig. 1. The energy generated by oxyhydrogen fuel cells and lithium batteries are reasonably configured, which ensures the high energy density requirements of underwater power stations. The system is designed to withstand a standard pressure chamber with a water depth of 300 m. According to the function, three pressure chambers are arranged, including fuel cell cabin, battery electrical cabin and drainage cabin. In the fuel cell cabin, a set of hydrogen and oxygen fuel cell system with zero exhaust emission is realized to meet the operation requirements of closed cycle of underwater environmental charging power station system. In the battery electrical cabin, the power supply generated by the two kinds of energy is charged in parallel by the power electronic device.



**Fig. 1.** Underwater high energy density fuel cell charging station system

## 2 Analysis of Factors Affecting Energy Density of Charging Station

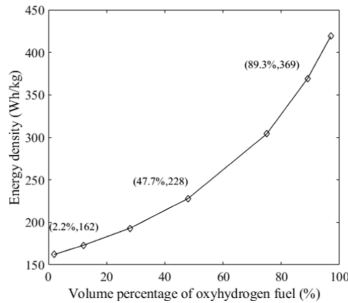
### 2.1 Theoretical Analysis of Energy Allocation

Assume that a 20-foot 5.8 m \* 2.3 m \* 2.3 m container is used as the integration framework of the charging station. High pressure hydrogen storage and oxygen storage are selected as the energy storage methods for hydrogen and oxygen fuel. Assume the high pressure gas cylinder is 35 MPa/162 L gas cylinder with length of 1840mm and outer diameter of 410 mm. The lithium battery is a lithium iron phosphate battery pack with volume capacity of 270 Wh/L and energy density of 160 Wh/kg. In terms of energy space layout,

the lithium battery pack is arranged as a whole battery package, and the hydrogen and oxygen fuel is arranged in a modular way of “cylinder plus frame”. The volume ratio of the hydrogen and oxygen fuel modules to the charging station is calculated, and the energy density of the charging station under different proportion conditions is analyzed.

Through the above calculation, the energy density of the whole charging station is obtained when the volume of oxyhydrogen fuel modules accounts for the proportion of the total volume of the whole charging station, and the change trend of the system energy density of oxyhydrogen fuel and lithium battery under different energy ratios is obtained, as shown in Fig. 2. It can be seen that the larger the volume of oxyhydrogen fuel modules, the higher the energy density of the whole charging station.

Therefore, in order to improve the energy density of the charging station, space of oxyhydrogen fuel modules should be increased as much as possible in combination with the characteristics of the platform structure. The energy transferred from oxyhydrogen fuel cells should also be the preferred energy source in the charging station system operation strategy.

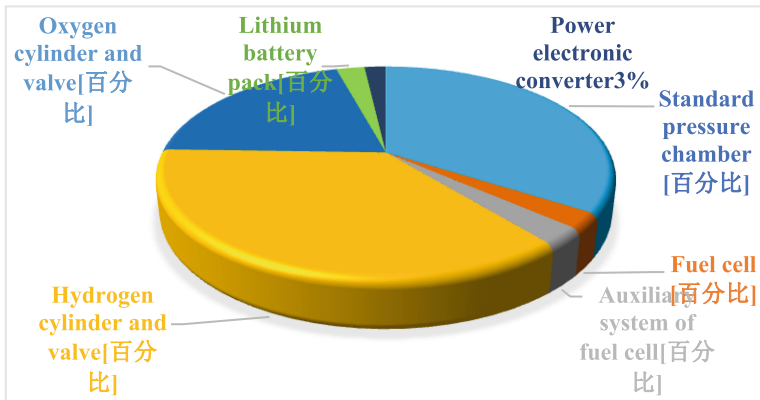


**Fig. 2.** Trend chart of oxyhydrogen fuel volume proportion and energy density of charging station

### 2.2 Theoretical Analysis of Weight Proportion

The charging station system mainly involves five parts: standard pressure chamber, oxyhydrogen fuel cell and its auxiliary system, oxyhydrogen fuel storage modules, lithium battery pack and power electronic converter. In order to deeply analyze the weight of each equipment, the weight specification parameters of each system and equipment were estimated during the design process, and the weight proportion of each system and equipment was calculated, forming the platform weight proportion analysis chart, as shown in Fig. 3.

According to the weight proportion analysis chart of each system and equipment, the proportion of hydrogen cylinders and valves, oxygen cylinders and valves, and standard pressure chamber occupies the top three, and the sum of the three accounts for more than 90% of the total weight, which is the key factor affecting the energy density of the entire system, Therefore, in the design and selection of hydrogen and oxygen storage modules and standard pressure chamber, the design principle of lightweight should be thoroughly implemented. Hydrogen and oxygen fuel cells, fuel cells auxiliary system,



**Fig. 3.** Analysis of weight proportion of components and equipment

lithium batteries and power electronic converters each account for between 2% and 3% of the whole platform. The hydrogen and oxygen fuel cells and their auxiliary systems are in one pressure chamber, and the hydrogen and oxygen fuel cells account for about 50% of the weight of the fuel cell system, the lithium cells and power electronic converters are in another pressure chamber, and the lithium cells account for about 50% of the total weight of the equipment. As the core of the charging station, the lightweight design of oxyhydrogen fuel cell and lithium battery has a great impact on the weight reduction of the two core chambers.

### 2.3 Design Principles for Improving Energy Density

In order to improve the energy density of the charging station, the project takes into account the system design and equipment selection from several aspects such as the energy configuration of oxyhydrogen fuel modules and lithium battery, system function, material and component lightweight. It includes the following principles:

- (1) Energy allocation: the capacity of lithium batteries should meet the basic requirements of the charging station control system for continuous power supply. In combination with the structural characteristics of the integration framework, hydrogen and oxygen fuel modules should be arranged as much as possible, in order to increase the proportion of hydrogen and oxygen fuel in the storage energy of the charging station, so as to improve the energy density of the system.
- (2) System functions: adhere to the simplest way to achieve all the essential functions, reduce the number of components or parts, and thus reduce weight at the functional level. Deeply analyze and demonstrate the redundancy function, and minimize the redundancy design. On the basis of realizing the functions, the simplest structure is adopted to realize the lightweight of the overall structure of the charging station [3].
- (3) Lightweight materials: on the premise of meeting the use requirements and reasonable redundancy, select the light material that meets the strength. The weight reduction of materials can be achieved by cutting the weight reduction hole in the plate, drilling the weight reduction hole in the square tube, and hollowing out the

plate to maximize the material performance. For parts such as pressure chambers that have a great impact on the weight of the system, the material shall be reasonably selected considering corrosion resistance, safety and lightweight.

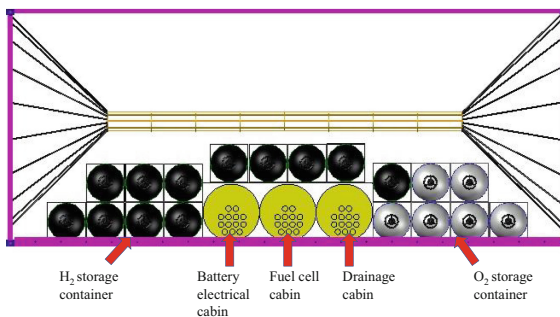
- (4) Lightweight components: for a large number of hydrogen and oxygen cylinders and valves, new lightweight materials such as carbon fiber should be actively explored. The lightweight design of hydrogen and oxygen fuel cells should be achieved by introducing new lightweight materials such as composite carbon fiber materials. Lightweight plastic products should be chosen as much as possible in the gas-liquid separator.

### 3 Design of Hydrogen and Oxygen Fuel Cell Charging Station System

#### 3.1 Maximum Configuration Structure Design of Hydrogen and Oxygen Fuel

In the integrated frame of the 20-inch container, combined with the structural characteristics of the charging station, high-pressure hydrogen and oxygen storage containers are arranged below, using domestic 35 MPa carbon fiber III bottles, the inner layer is sealed with aluminum tank gas, the middle layer is carbon fiber reinforced resin to ensure the compressive strength, and the surface layer is glass fiber reinforced resin layer to protect the surface. Combined with the marine environment, carbon fiber high-pressure gas cylinders have excellent corrosion resistance characteristics, acid, alkali, salt and atmospheric corrosion resistance, and are safer to use [4].

At present, the general product is type III carbon fiber gas cylinder with a pressure resistance of 35 MPa. The conventional product is 162 L, with a valve length of 1830 mm and an outer diameter of 410 mm. This type of gas cylinder is selected as a high-pressure hydrogen and oxygen storage container. After three-dimensional modeling and calculation, a total of 18 hydrogen and oxygen gas storage containers with the specification of 35 MPa/162 L can be arranged, as shown in Fig. 4. Among them, 12 hydrogen gas storage containers are distributed on the left and upper sides of the pressure chambers, and 6 oxygen gas storage containers are distributed on the right side of the pressure chamber.



**Fig. 4.** The maximum configuration of hydrogen and oxygen gas storage vessels in the overall structure of the platform

### 3.2 Hydrogen and Oxygen Fuel Cell and Its Auxiliary System Design

Hydrogen and oxygen fuel cell and its auxiliary system mainly include hydrogen and oxygen fuel cell, hydrogen supply cycle system, oxygen supply cycle system, cooling cycle system, water collection system, hydrogen and oxygen tail gas absorption system and control system, as shown in Fig. 5 [5, 6]. The various components of system are arranged in the closed chamber with the specified space length  $\leq 1500$  mm and inner diameter  $\leq 570$  mm in the pressure chamber, to ensure the separation of gas, water and electricity, and to disperse the heat generated by the hydrogen and oxygen fuel cell in time, and to ensure that the liquid water generated can be discharged in time. The oxyhydrogen fuel cell and its auxiliary system have adopted compact design and lightweight design to comprehensively improve the energy density of the oxyhydrogen fuel cell and its auxiliary system.

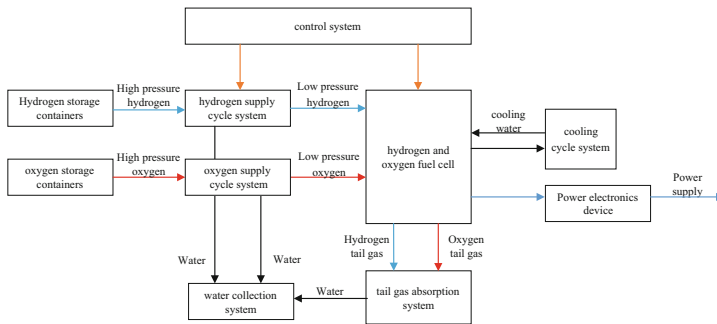


Fig. 5. Schematic diagram of oxyhydrogen fuel cell and its auxiliary system

#### (1) Compact design

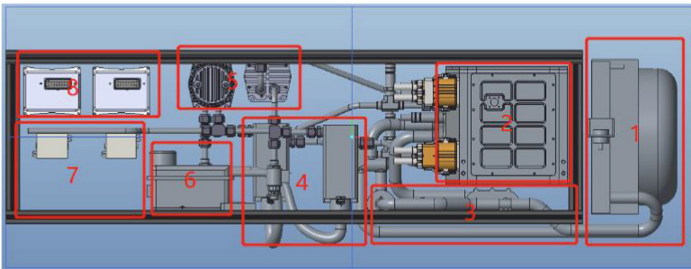
In the fuel cell cabin, the size of the pressure chamber is taken as the size boundary of the layout, and the reasonable layout is divided into eight areas, as shown in Fig. 6, which ensures the separation of gas, water and electricity, and at the same time, the heat generated by the hydrogen and oxygen fuel cells can be dispersed in time.

The radiator (area1) is arranged on the right side of the system, and stuck to the surface of the pressure chamber, making full use of the low temperature sea out of pressure bulkhead for heat dissipation. Considering that the interfaces of the gas, electricity and the cooling of the oxyhydrogen fuel cell are all integrated on the left side, the oxyhydrogen fuel cell is set at the rightmost end of the frame (area 2). The cooling cycle system, including water pump, deionizer and thermostat, is arranged at the lower side of the oxyhydrogen fuel cell (area 3), which reduces the electrical risk caused by leakage and makes comprehensive use of the bottom space.

Gas-liquid separator and three-way pipeline are arranged in the middle of the cabin (area 4). The gas-liquid separator is arranged at the bottom of the system to facilitate the collection of water. The hydrogen and oxygen supply cycle systems, including supply pipeline, gas circulation pump and three-way pipeline, are arranged in the middle and

upper part of the pressure chamber (area 5). The hydrogen and oxygen fuel cell considers the convenience of water management, and the gas circuit adopts the cycle way of upper inlet and lower outlet. Water collection system is arranged in area 6, including water tank and drainage pump.

The control system is arranged on the left side of the pressure chamber (area 7) to integrate the system controller and power supply module. The left side is close to the pressure chamber flange, which is convenient for the external output and connection of the system cable. The hydrogen and oxygen tail gas absorption system is arranged at the left upper part of the pressure chamber (area 8), including the hydrogen and oxygen absorber, fan, hydrogen concentration sensor and pipeline. Considering the low hydrogen density, leakage is easy to gather on the top. When exhaust gas needs to be treated, the fan is used to circulate the mixed gas in the forced sealing chamber through the hydrogen and oxygen absorber and undergo catalytic combustion to consume hydrogen and oxygen in the chamber.



**Fig. 6.** Compact design of oxyhydrogen fuel cell and auxiliary system

## (2) Lightweight design

The lightweight design of the fuel cell system has been realized by adopting six series aluminum alloy hollow frame structure, lightweight hydrogen and oxygen fuel cell, and new normal temperature hydrogen eliminator.

Since the oxyhydrogen fuel cell and auxiliary system are arranged inside the pressure chamber, all equipment and components are installed on the integrated frame, which adopts a hollow frame structure, reducing the weight of the entire frame. The frame is made of six-series aluminum alloy. Six-series aluminum alloy is the most widely used alloy with magnesium and silicon as the main added elements and  $Mg_2Si$  as the main strengthening phase. 6061 and 6082 aluminum alloys in the six-series aluminum alloys are heat-treatable and can be strengthened. They have good formability, weldability, machinability, and medium strength. They can still maintain good operability after annealing. It is widely used in various industrial structural parts requiring certain strength and high corrosion resistance.

The stress distribution of the end face structure of the oxyhydrogen fuel cell is determined by simulation, and the reduction preparation method is adopted to reduce the end face materials as much as possible, and then the weight reduction goal is achieved

by introducing new lightweight materials such as composite carbon fiber materials; At the same time, it forms a unified design with the end face fluid distribution port, connector and sensor structure attached to the oxyhydrogen fuel cell to realize the function and structure modularization.

At present, the commonly used hydrogen removal methods include catalytic combustion, alloy hydrogen storage and auxiliary hydrogen and oxygen fuel cell absorption [7, 8]. For large-capacity power generation system, multiple hydrogen storage alloy devices will be equipped, greatly increasing the size and weight of the equipment. The auxiliary hydrogen and oxygen fuel cell absorption method needs to be equipped with auxiliary small fuel cells, which are connected in series with the fuel cell body used for power generation to consume the remaining anode gas and cathode gas in the reaction of the fuel cell body used for power generation. The auxiliary hydrogen and oxygen fuel cell needs to be equipped with gas supply system, cooling system, etc. to achieve a large number of components, the overall system is relatively complex, and the efficiency is low, which needs to occupy a large amount of volume space. The hydrogen removal method adopted in this system is to directly pass the hydrogen-containing mixture into the catalytic device at low temperature or normal temperature, without external heat source heating, and the heat generated by the catalytic process can accelerate the hydrogen removal reaction rate. The hydrogen removal device adopts compact and miniaturized design, with catalytic efficiency of more than 95% and weight of only 800 g. There is no need to replace or supplement hydrogen removal substances and desiccant, which eliminates replacement/supplement operation steps, prolongs the operation cycle of the system and reduces the maintenance cost.

### 3.3 Standard Pressure Chamber Design

Considering the working water depth of the charging station, the cylindrical structure is adopted in the structure shape, the end of one side is welded with a cover plate, and the end of the inlet and outlet cables is sealed and installed with a flange plate. The pressure chamber is designed as a cylinder, which is mainly based on the advantages of high radial pressure resistance, low axial underwater upstream resistance, and easy processing. The pressure chamber prototype is composed of a cylinder, two end covers and watertight connectors on the end cover. Each end cover and cylinder are connected uniformly on the circumference with screws, and the end face is sealed with O-ring. The pressure chamber of its underwater charging station is shown in Fig. 7.

The pressure chamber is made of 6061 aluminum alloy. As the pressure water depth is not less than 300 m, the working pressure  $p_w$  is 3MPa, that is, the design pressure of chamber  $p_c = 1.1p_w = 3.3$  MPa. According to the national standard GB 150.1-150.4-2011 <Pressure Vessel>, the cylinder thickness is calculated according to the strength failure design:

$$\delta = \frac{p_c D_i}{2[\sigma]'\phi - p_c} = 11 \text{ mm}$$

The specific meaning of parameters in the formula is as follows:

$p_c$ -design pressure of chamber, 3.3 MPa,



$D_i$ -inner diameter of pressure chamber, 570 mm,  
 $[\sigma]^t$ -allowable stress of the material, take  $[\sigma_d]$  and  $[\sigma_b]$  minimum value, 96.7,  
 $\phi$ -the welding coefficient, 100% NDT is required for single butt joint, 0.9.

Considering that the roundness of the cylinder can not be guaranteed by actual machining, and there are uneven factors such as material and load distribution, combined with machining allowance, corrosion allowance and screw connection,  $\delta$  is taken 20 mm, then the outer diameter of pressure chamber cylinder is 610 mm.

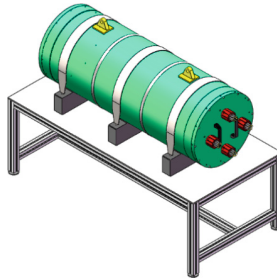


Fig. 7. 3D design drawing of pressure chamber of underwater charging station

#### 4 Calculation of Energy Density of Charging Station System

The number of hydrogen moles is calculated by van der Waals gas equation. The hydrogen enthalpy value is used and the hydrogen fuel energy is calculated according to the efficiency obtained at the working point of the hydrogen and oxygen fuel cell. The project adopts a hydrogen cylinder with a volume of 162 L and a pressure of 35 MPa, which is substituted into the van der Waals gas equation:

$$\left(P + \frac{n^2 a}{V^2}\right)(V - nb) = nRT$$

The specific meaning of parameters in the formula is as follows:

- $P$ -Gas cylinder storage pressure, 35,000kPa,
- $V$ -Nominal volume of gas cylinder, 162 L,
- $a$ -parameter to measure intermolecular gravity, 24.32,
- $b$ -Sum of volumes of one mole of molecules, 0.027 L/mol,
- $n$ -molar weight, mol,
- $R$ -ideal gas constant, 8.314 J/(mol K),
- $T$ -temperature, 273.15 K.

Molar weight can be obtained by substituting the parameters.

$$n = 1876 \text{ mol}$$

According to the hydrogen low enthalpy value of 241 kJ/mol and the efficiency of hydrogen and oxygen fuel cell of 50%, the hydrogen fuel energy is calculated as follows:

$$Q_0 = \frac{\eta * n * q_{H2}}{3600} = 62.8 \text{ kWh}$$

It can be concluded that the complete consumption of hydrogen can provide 62.8 kWh of electric energy. The number of hydrogen cylinders is 12, and the calculation of all hydrogen fuel energy is

$$Q_1 = 12 * Q_0 = 753.5 \text{ kWh}$$

The lithium-ion battery pack with weight of 35 kg and storage capacity of 5 kWh is selected. Then the total energy reserve of the charging station is

$$Q = Q_1 + Q_2 = 758.5 \text{ kWh}$$

The system and equipment involved in the weight of the charging station, including the pressure chamber, the oxyhydrogen fuel cell and its auxiliary system, high pressure fuel cylinders under full load, the lithium battery pack and the power electronic converter, have been physically checked according to the weight of the prototype, and the results are shown in Table 1.

**Table 1.** Weight of five system and components

Code	Item	Number	Weight (kg)
M1	Pressure chamber	3	708
M2	Fuel cell and its auxiliary system	1	122
M3	High-pressure gas cylinders	12 + 6	1836
M4	Lithium battery pack	1	35
M5	Power electronic converter	3	46
M	Total		2747

The energy density of the underwater charging station is calculated as follows:

$$\rho = \frac{Q}{M} = 276 \text{ Wh/kg}$$

## 5 Conclusion

This paper designs an underwater high energy density fuel cell charging station system with hydrogen and oxygen as the main energy. By reasonably configuring hydrogen and oxygen fuel modules and the lithium batteries, the energy density of the underwater hydrogen and oxygen fuel cell charging station is 276 Wh/kg, and the main indicators of the system are shown in Table 2.

In the calculation process, although a large number of documents and materials have been consulted and the basic theories and related technologies of fuel cells and lithium batteries have been carefully studied, there are still some problems to be improved and further discussed, which can be summarized as follows:

**Table 2.** Main indicators of the system

Item	Number
Total weight	2747kg
Hydrogen energy	753.5 kWh
Lithium battery energy	5 kWh
System energy density	276 Wh/kg
Size of fuel cell chamber	Length 1500 mm, inner diameter 570 mm
Fuel cell output power	5 kW
Cylinder size	Length 1830 mm, outer diameter 410 mm

The calculation of hydrogen fuel energy is mainly based on the theoretical calculation of the van der Waals ideal gas formula, and the actual power generation of hydrogen fuel has not been tested and verified. The calculation results may differ from the actual operation data. In the next step, the hydrogen fuel energy will be further tested and verified in combination with the demonstration and verification system prototype.

This paper calculates the energy density of the system from the perspective of hydrogen storage and lithium battery storage, and assumes that all the energy is used for charging. It does not consider the specific charging and discharging operating conditions between the power generation end and the load end, nor does it consider the efficiency of electric energy in the transmission process. Therefore, it is necessary to further refine the power transmission efficiency according to the actual application.

These are the problems that need to be studied and solved in the future research. It is believed that with the development of hydrogen fuel and lithium battery energy storage technology and its application in underwater charging stations, the energy density of charging stations will make greater progress.

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